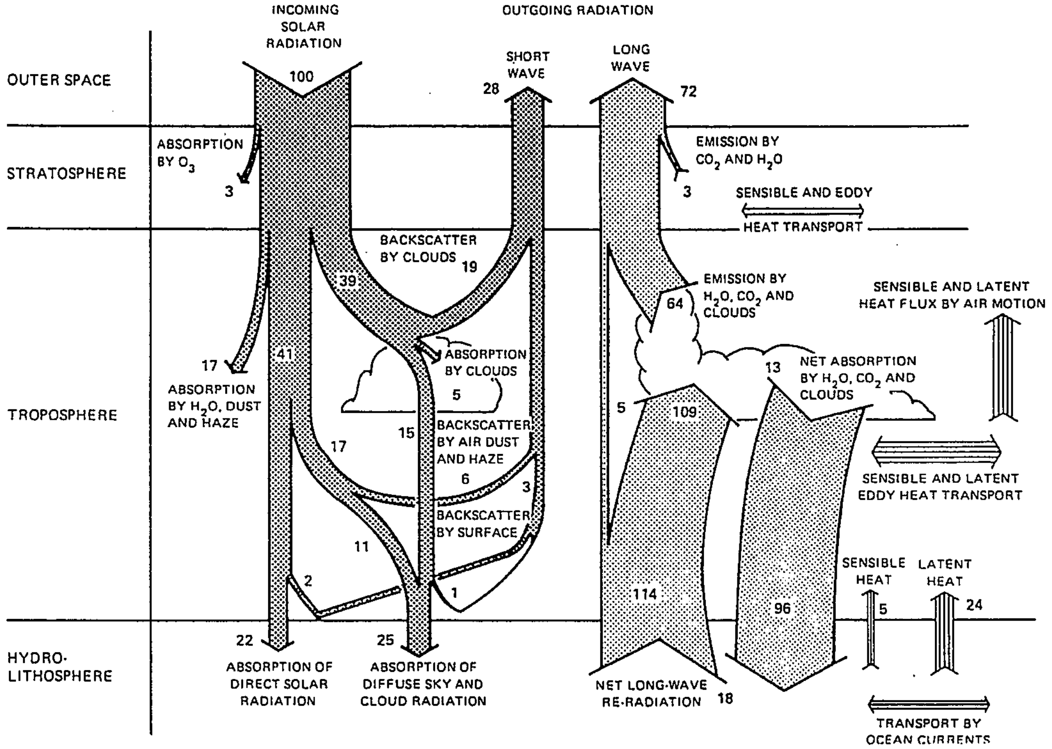
Teacher Background Information: The Earth's Radiative Heat Budget

The energy from the Sun is the principal power behind the Earth's systems. The various energy flows and storages in and between each of the Earth's subsystems - *the planetary energy balance*- involve many components. Each of these items represents either input of radiation to the planet (solar heating), its output from the planet (infrared cooling), storage or release of heat within the climate system (evaporation, condensation, melting and freezing), or transport of heat from one part of the climate system to another (wind and ocean currents). Taken together, these processes serve as the driving forces of the climate system. The overall energy available to drive all climatic processes on a planetary scale principally comes from the distribution of radiation arriving from space and leaving from the Earth- the *radiation balance.*



The annual mean global energy balance for the Earth-atmosphere system.

The Earth intercepts an extremely tiny fraction of the total energy continuously emitted by the Sun. Of the roughly 380 trillion (3.8 x 10^{26}) watts of power radiated by the thermonuclear reactors of the Sun, our planet intercepts less than one ten millionth of 1 percent (about 4.5 x 10^{-8} percent). If all of this energy averaged over a one year period were distributed uniformly across our planet's surface, it would amount to about 345 watts for every square meter of the Earth at any one instant. Since an adult human being produces roughly 100 watts of metabolic energy from "burning" his or her food, this means that the Sun puts as much heat, on average, into the planet as if there were 3-4 people standing on every square meter of Earth. This 345 watts per square meter of solar energy reaching the Earth's surface is referred to as the *earth-averaged solar constant.*

If Earth only absorbed radiation from the Sun without giving an equal amount of heat back to space by some means, the planet would continue to warm up until the oceans boiled. Satellites have shown that the Earth's temperature remains relatively constant from year to year. This constancy requires that about as much radiation leave the planet each year in some form as is coming in. In other words, an *equilibrium or energy balance* are crucial to the climate.

All bodies with temperature give off radiant energy. The Earth gives off a total amount of radiant energy equivalent to that of a black body with a temperature of about 255 K (-18 C). The wavelength that is in the maximum part of the spectrum of energy emission for a 255 K black body is about 10000nm, in the middle of the far infrared frequencies. Nearly all of the energy emitted by the Earth's surface and its atmosphere falls in the far infrared range between 5000 and 1000 nm and is known as *terrestrial infrared radiation.* Although we can't see it, this terrestrial radiation emitted to space by the planet is nearly balanced each year with the amount of absorbed solar radiation - the equilibrium required to make the Earth's climate relatively stable. If the Earth's albedo were somehow to drop, the darker planet would absorb more insolation and heat up. As it got hotter, more terrestrial radiation would be emitted to space until eventually, a new, but warmer, equilibrium would be established.

Although most of the Earth's surface and thick clouds are reasonably close approximations to a black body, the atmospheric gases are not. When the radiation emitted by the Earth's surface travels upward in the atmosphere, it encounters air molecules and aerosol particles. Water vapor, carbon dioxide, methane, nitrogen dioxide, ozone and many other trace gases tend to be highly selective, but often highly effective, absorbers of terrestrial infrared radiation. In addition, clouds absorb nearly all of the infrared radiation that hits them, and then reradiate it. The effect of the clouds and the gases in the atmosphere is to reduce by a large fraction the amount of infrared radiation that would otherwise escape to space. It results in a large downward atmospheric emission of infrared energy to the surface- 114 units of radiation go up, but 96 units (nearly 85%) are reradiated to the surface.

The atmosphere is more opaque to terrestrial infrared radiation than it is to incoming solar radiation, simply because the physical properties of the atmospheric molecules and particles tend on average to be more transparent to solar radiation than to terrestrial radiation. These properties create the large surface heating that characterizes the greenhouse effect, by which means the atmosphere allows a considerable fraction of solar radiation to penetrate to the surface and then intercepts and reradiates much of the upward terrestrial infrared radiation from the surface and lower atmosphere. The downward reradiation, in turn, further enhances surface warming.

The Earth' temperature is primarily determined by the planetary radiation balance, through which the absorbed portion of the incoming solar radiation is nearly exactly balanced over a years time by the outgoing terrestrial radiation emitted by the climate system to space. As both of these quantities are determined by the properties of the atmosphere and the Earth's surface, major climate theories that address changes in these properties have been constructed and remain plausible hypotheses of climatic change.

As the spectrum of solar energy strikes the Earth, some of it is absorbed, some of it is scattered, and some of it is transmitted directly to lower levels of the atmosphere. The absorption, scattering and transmission are selective, and do not occur uniformly within the atmosphere. Various molecules, particles or surface features absorb, scatter or transmit energy with very different efficiencies, depending upon the wavelengths of the transmitted energy. For example, most of the radiation with wavelengths shorter than 100nm is absorbed above 100km in the atmosphere by N_2, O_2, N, O and their ions. At longer wavelengths, O_2 becomes a weak absorber, and O_3 assumes the role of major absorber of radiation in the 210-310 nm band. This ozone absorption provides the energy which heats the stratosphere and much of the mesosphere. It also provides a screening of incoming UV radiation which is responsible for biological mutations, sunburn and other physiological effects.

All molecules tend to scatter radiation, and the character of the scattering depends upon the wavelength of the radiation relative to the size of the molecules or other particles in the atmosphere. The molecules that compose the gases of the atmosphere are all very small relative to the wavelengths of most sunlight. For this reason, shorter wavelength radiation is scattered more effectively than longer wavelengths through a process known as *Rayleigh scattering.* The sky is blue because the scattering of sunlight by the many tiny molecules of the Earth's atmosphere favors shorter wavelengths, such as blue light. For the much larger particles, such as soil dust or sulfuric acid, which make up *atmospheric aerosols*, the scattering efficiency is much more uniformly distributed across the visible wavelengths. Some of the scattering from clouds and dust results in *back-scattering,* whereby a fraction of the incoming solar energy is scattered back, or reflected to space. The fraction of solar energy reflected back to space by the Earth-atmosphere system is called the *planetary albedo.*

Gases and particles in the atmosphere tend to be fairly transparent to much of the solar radiant energy, allowing about half of the solar rays to pass through to the Earth's surface. However, not all of it passes directly through to the surface uninterrupted. Much of it - virtually all of it on a cloudy day - arrives as *diffuse radiation,* having been scattered by atmospheric particles and molecules. About one-third of the total of the Sun's radiant energy that reaches the Earth eventually hits the surface without being scattered and about one-quarter reaches the surface as diffuse radiation. There, some 85 percent of the total amount is absorbed. Over dark surface such as the oceans, more than 90 percent is absorbed; in the seas or in very wet vegetated areas this absorbed heat is used to evaporate water, Over bright surfaces, such as deserts and snowfields, 40-80 percent is reflected. Over deserts for example, as little as 1 percent of the absorbed energy is used to evaporate water; the rest simply warms the surface.

To summarize, a little less than a third of the Sun's radiation that reaches the Earth is reflected away, almost half is absorbed at the surface and the remaining 20 percent or so is absorbed by gases and particles in the atmosphere. The principle energy-driving mechanism of the climate system is the absorption of solar energy by the molecules and particles of the atmosphere and the surface features of the Earth.