Earth Energy Balance Exercise Instructor Notes

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The Earth energy balance exercise is based primarily on readings from Harte, J., 1988, Consider a Spherical Cow, Sausalito, CA: University Science Books, 283 p. In his book, Harte leads the reader through a derivation of Earth's surface temperature given the assumption that the planet acts as a perfect black body, reflecting and re-radiating all energy incident upon it from the Sun. The black body assumption allows one to calculate the equilibrium temperature for Earth from the Stefan-Boltzmann Law, which states that the energy given off by a black body is a function of its temperature:

$$E = \sigma T^4$$

where E is the energy given off by the black body, σ is the Stefan-Boltzmann constant ($5.67e^{-8}$ W/m^2K^4), and T is the temperature in Kelvin. Since a black body gives off as much energy as it absorbs, the equilibrium temperature can be determined by equating the energy absorbed from the Sun (S) to the right hand side of the equation above:

$$S= \sigma T^4.$$

S has a measured value of 1370 W/m^2 at the Earth's position in the solar system. Radiation falls off via an inverse square law such that

$$S_1 r_1^2 = S_2 r_2^2$$

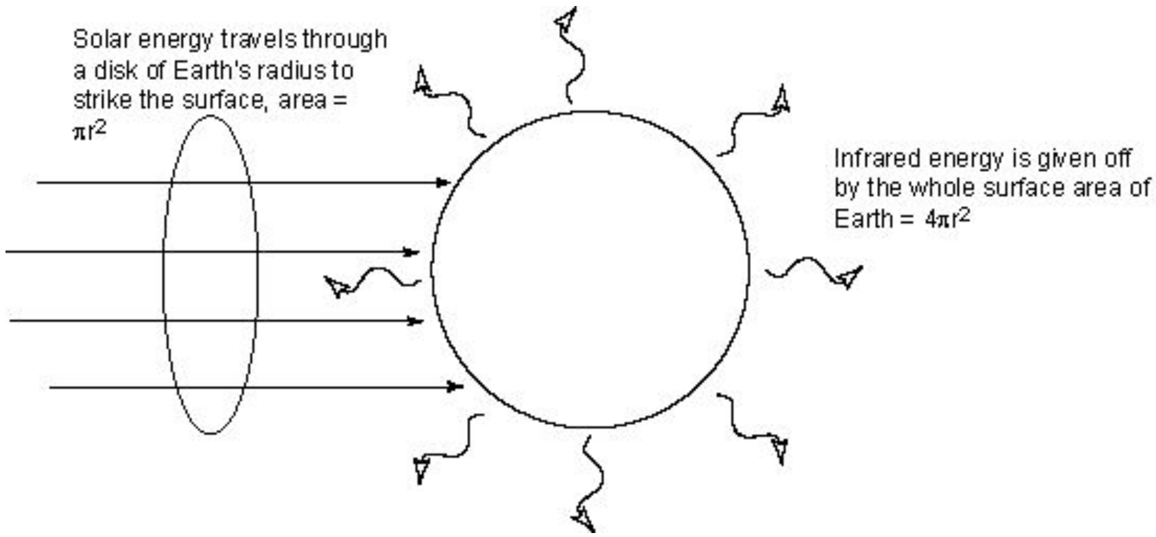
where S is the solar constant, r is the distance between the planet and the Sun, and 1 and 2 refer to any planet. One can use this relationship along with the known planetary distances from the Sun to determine the solar constant for any other planet in the solar system. The exercise I've created could therefore be modified to explore other planets.

A related law, known as Wien's displacement law relates the wavelength of peak energy emission to the black body temperature in Kelvin:

$\lambda_{peak} = 2897./T$ units of wavelength are micrometers

Given the solar constant for Earth of 1370 W/m^2, the radiative equilibrium temperature for the planet is 255 K, and this puts the wavelength of peak radiation in the infrared part of the electromagnetic spectrum.

Casting the black body Earth problem in STELLA terms requires the creation of a reservoir into which the incoming solar energy flows and out of which the emitted infrared energy flows. Since the flows of energy into and out of this reservoir are measured in W/m^2, the reservoir itself contains $Joules/m^2$ (1 Watt = 1 Joule/second). To make the problem more tractable, it's easier to conceive of the flows as coming in Joules per year, which requires multiplying the solar constant by the cross-sectional area of the Earth (see figure on next page) and the outflow from the Stefan-Boltzmann law by Earth's surface area. In addition, both flows need to be multiplied by the number of seconds in a year. As a result of multiplying the flows by these areas and by seconds/year, the reservoir contains only Joules of energy. This then allows a very straightforward calculation of planetary temperature. One need only divide the energy contained in the reservoir (J) by its heat capacity (J/K).



In the model in this exercise, we follow the lead of Arthur Few, 1996, System Behavior and System Modeling, Sausalito, CA: University Science Books, 100 p., and conceive of the Earth's surface as a "swamp" of water 1 meter deep. The swamp assumption allows the heat capacity (c) to be calculated from the following:

$c = d * A * \rho * sh$

where d is the depth of water in meters, A is the surface area of Earth ($4\pi r^2$), ρ is the density of water, and sh is its specific heat.

Because this model reflects equilibrium (steady state) between inflowing and outflowing energy and because the inflows remain constant, the ultimate temperature reaches the same value regardless of layer thickness, density, and specific heat. In other words, one achieves the same result whether one uses a 10 cm thick layer of water or a 20 m thick layer of rock. Where the type of material is important is in the time required to reach steady state. The smaller the heat capacity of the material, the more quickly the surface temperature reaches the steady state value. Though I do not currently have students explore this aspect of the model, it could easily be incorporated into the exercise.

Once the basic black body radiation model is created, students build upon this model to explore the impact of albedo and of the atmosphere on Earth's surface temperature.

The primary purpose of the Earth Energy Balance exercise is to convey the importance of starting out simply when creating models and adding complexity gradually. I have found that most of my students try to toss in everything but the kitchen sink when they first begin working on their independent projects. They get lost in trying to get the fine points of their models to work and typically end up neglecting to see if the main architecture of their models is working correctly. When this happens, I ask them to reflect on the Earth energy balance model lab in which we built complexity very gradually and then ask them to try to pick out the most fundamental processes that they're trying to model in their chosen problems.