World of Light - Problem Set #7

Due at start of class on ***Wed. June 3.***

Reading

Light Science section 6.1.

Topics and equations

In this problem set, you will predict the average temperature of the Earth, not accounting for the greenhouse effect. You will then quantify the greenhouse effect and then see how the temperature changes when the greenhouse effect is enhanced. It requires the use of the following constants and equations:

speed of light in vacuum = $c = 3\times10^8$ m/s
Stefan-Boltzmann constant = $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}

$$E = \sigma T^4 \qquad \lambda_{max} = \frac{2.898\cdot10^6 \text{ nm K}}{T}$$

sphere surface area = $4\pi r^2$
circle area = πr^2
temperature in K = °C + 273

Problems

Show your work for all problems! *Grading scale: basically right = 1 point, basically wrong = 0 points, some right and some wrong = 0.5 points; no finer gradations.*

1. *Temperature of the sun*. The peak of the solar emission spectrum is at 502 nm. Using this, what is the temperature of the surface of the sun?

2. *Sun surface power*. Using the sun surface temperature that you just computed (which should be about 5773 K), how much radiant power does the sun emit from each square meter of its surface?

3. *Total sun power*. The sun radius is about 696,000 km. (a) What is the sun surface area in square meters? (b) Using your answer from problem 2 (which should be about 6.3x10^7 W), how much total power does the sun emit over its entire surface?

4. *Flux of sunlight at Earth*. Next, we want to calculate how much power is in a square meter of sunlight, at the Earth. To do so, imagine an entire sphere placed around the sun that has the radius of the Earth's orbit (149,500,000 km). (a) What is the surface area of this sphere, in m^2? (b) How much power goes through each square meter (divide the total sun's output power by this number of square meters)? This is called the solar constant.

5. *Projection effect*. In the last problem, you should have found that the solar constant is about 1367 W of power in each square meter at the Earth. It is for a square meter that is oriented exactly towards the sun. Now, let's convert this to the power for an average square meter of the Earth's surface, which is not necessarily oriented directly at the sun. (a) Using the fact that the Earth's radius is 6371 km, what is the area of sunlight that

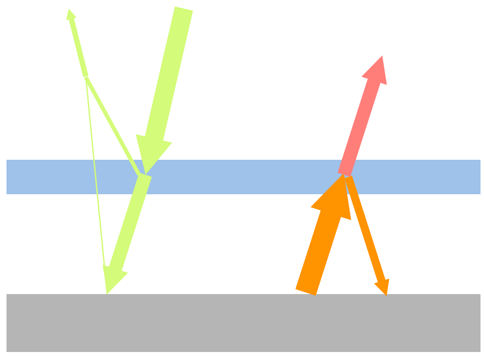
strikes the Earth? The idea here is that the same amount of sun hits the Earth as would hit a disk of this area. (b) What is the total Earth surface area, now treating the Earth as a sphere? (c) What fraction of the maximum possible sunlight hits an average square meter of the Earth's surface (divide the answer for part a by that for part b)? (d) What is the incident sunlight on an average square meter of the Earth's surface (multiply the solar constant by the answer for part c)?

6. *Earth albedo*. You should have found that the sun's power on an average square meter of the Earth is about 342 W. About 30% of this light reflects off of clouds, the oceans, snow, and light colored sand without being absorbed. (a) What is the power of the light that is reflected? (b) What is the power of light that is absorbed?

7. *Earth emission*. In the last problem, you should have found that the incoming solar radiation is about 239 W. The Earth is a "steady-state" system, meaning that it is neither gaining nor losing energy. Thus, each square meter of the Earth's surface must also emit about 239 W of energy. (a) What is the temperature, in K, of a square meter that emits about 239 W? (b) What is this in Celsius? (c) What is wavelength of maximum emission for light from the Earth?

8. *The greenhouse effect*. In the last problem, you should have found that the Earth's temperature would be about -18° C if it didn't have a greenhouse effect. Alternatively, this actually is the average temperature on the surface of the Moon, where there's no atmosphere. However, on Earth, the actual average temperature is about 16° C. (a) How much warmer is the Earth than what it would be if it didn't have an atmosphere? (b) How much energy is radiated from 1 square meter of the Earth's surface, using the actual Earth surface temperature? (c) How much power does the atmosphere send back to the Earth's surface? To calculate this, assume that the atmosphere isn't gaining or losing energy; if it's losing 239 W to space, from problem 5b, and it's gaining the amount of energy that you calculated in part b of this problem, then the difference must be the amount of energy that it sends back to Earth's surface. (d) What fraction of the energy emitted from the Earth's surface gets reflected back to Earth (i.e. the ratio of the two prior numbers)?

9. Shown below are two figures. The first is a diagram of the numbers that you computed and the second is from a recent review article which shows the best current scientific understanding (Trenberth, Fasullo, and Kiehl, *American Meteorological Society*, 2009). (a) Copy over the first figure and write your numbers next to the arrows as appropriate. (b) Which numbers in the second figure are essentially identical to the ones that you calculated? (c) What are the main differences between the processes that the two figures accounted for?



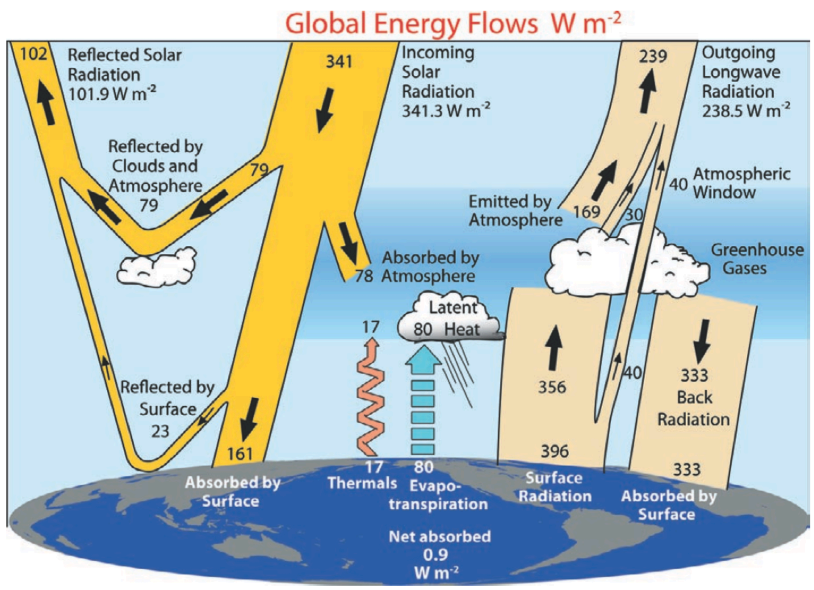


Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

10. *Global warming*. You should have found in problem 8d that about 40% of the radiation that the Earth emits is sent back to the Earth, meaning that about 60% of the energy escapes to space. Suppose the atmospheric reflectivity increased by 2%, so now 42% of the light returns to Earth and 58% goes to space. (a) How much radiation must go from Earth to the atmosphere (the outgoing radiation is still 239 W from problem 6b, so divide this by 58%)? (b) What is the increased Earth temperature? (c) By how many degrees did this atmosphere change warm the Earth?