“What matters is what’s in your head” Linus Pauling

“He was like an alcoholic, with bottles stashed everywhere within arms reach of any chair in the house. Every number was near some number he knew.” James Gleick on Hans Bethe

Go over stuff from last time.

Chemical structure of the earth
Production of oceanic and continental crust by fractional melting
Convergent, divergent, and transform plate boundaries

Key concepts for this lecture:

The origin of Radiant energy and Light
Radiational equilibirum
Greenhouse Effect
Quantitative relationship between temperature and radiant energy

Goals:

1) calculate the surface temperature of the sun given the solar flux at the earth
2) calculate the surface temperature of earth in radiational equilibrium with the sun
3) calculate the amount of ocean water evaporated in one year by the sun
4) calculate how long it takes to evaporate the oceans

By the way, we do our quantitative stuff here, in class for fun. I hope to instill in you a spirit of adventure in this regard. For this reason we don’t do this kind of thing on a test. My tests in this class will be multiple choice, and focus almost entirely on having a feel for the numbers we calculate in class (when we do quantitative things in class, which, unfortunately, will not be too often)

Lecture 3. The external engine of the atmosphere and hydrosphere

Last time we talked about the internal “heat engine” of the earth and how heat generated by radioactive decay in the interior of the earth resulted in convection, a mechanical motion which drives the plates around on the surface of the earth.   Today’s subject is the other heat engine that drives hydrologic/atmospheric circulation. The external heat engine interacts with the internal engine through its effect on the process of physico-chemical weathering which breaks down primary rocks into sediments and soils.

The behavior of the atmosphere/hydrosphere has special importance because its condition defines the Earth’s climate. In 1884 Svante Arrhenius at the University of Uppsala proposed that molecules could dissolve in water as separate, charged parts called ions.

His idea was coolly received by the chemistry faculty and he was barely awarded his doctoral degree. His thesis would get him the Nobel Prize twenty years later. In 1894 Arrhenius proposed that carbon dioxide accumulating in the atmosphere from the burning of fossil fuels could lead to global warming. To understand his arguments we have to review some important concepts about radiant energy and temperature.

What is light? Go through the idea of shaking an electrical charge on the end of a stick to produce the electromagnetic spectrum. It seems evident that these waves have to propogate in something. People used to think it was “the ether” now we say it is the electromagnetic field. Point out that this is quite an abstract idea. It was invented by a scot named James Clerk Maxwell in 1860. It is one of the most important concepts in all of science.

We are all aware that matter consists of lots of negative and positive charges in intimate contact. This intimacy is a result of the extremely strong electrical forces binding these charges together. Since heat is just the random kinetic energy associated with shaking and jiggling atoms, these charges are constantly in motion, and, therefore produce excitations in the electromagnetic field, which radiate away at the speed of light. Of course these same charges are coupled to any electromagnetic radiation that might be coming in from somewhere else. If the rate of heating from the incoming radiation exceeds the outgoing radiation, the charges will heat up, if it’s less, they cool down. Eventually equilibrium is reached.

You can guess that there is probably some definite relationship between the temperature (which governs the amount of jiggling of the charges), and the frequency of the light they “emit”, or, put differently, the frequency of the disturbances the make in the electromagnetic field.

A guy named Max Planck also thought as you might be thinking now, and worked out the relationship between the shaking charges and the light they emit. As you will learn in your physics class, the relationship turned out to be more complex than anybody would have imagined. But for now, we can understand that the flux of radiation should be proportional to the temperature (it turns out it is proportional to the fourth power of the temperature).

But wait, does all this radiation come off at one frequency? No, experimentally it was observed that the radiation was emitted over a range of frequencies. The range of frequencies changes as the temperature changes. What does this represent physically? Why would we expect this behavior? (Get the students to think about the atoms oscillating inside the material emitting light, and that the increasing heat excites new vibrations not accessible at lower temperatures). The higher the temperature, the higher the average frequency of the oscillations. This fact is crucial to understanding the functioning of the external engine.

SLIDE #1 Planck’s data.
SLIDE #2 Goodsteins Slide

We can skip the whole theoretical part of this and imagine that we could construct this relationship purely by experiment, just by heating things and measuring the spectrum of radiation as a function of temperature.

Do this maybe:

Flux = k * T^4. Where k is a fundamental constant equal to 5.67 x 10^{-8} Joules/Kelvin^4/m^2/sec. Mysterious, but reasonable. It might not have been expected that the flux is proportional to the fourth power of the temperature, but otherwise this is a pretty simple formula. It is also a useful one. For example: say you put a little light meter out about the atmosphere that measures the amount of energy given off by the sun. Lets say that device measures that right now that device tells us that the sun is producing 1372 watts/m^2. We could actually use that information to figure out the surface temperature of the sun, if we knew how far away it was.

The sun is 1.5 x 10^{11} m from earth. As energy is radiated away from the sun, it spreads out like the surface of a sphere. As you know, the surface area of a sphere is $4\pi r^2$. The sun's radius is 696,000,000 m. So the flux of energy at the surface of the sun is $(1.5 \times 10^{11})^2/(6.96 \times 10^8)^2$ or 46,450 times more concentrated than it is by the time it gets to the Earth

1372 Joules/m^2/sec x 46,450 = 63,700,000 Joules/m^2/sec

since

Flux = k * T^4,

$T=(\text{Flux}/k)^{1/4} = (63{,}700{,}000/(5.67 \times 10^{-8}))^{1/4} = 5790$ K.

Now talk about the difference between a person, a stove, and the sun radiating. Your atoms are shaking at a temperature of 98.6 F, and hence you are exciting the electromagnetic spectrum all the time, but at quite long invisible wavelengths. Your stove glows red because it is hot enough to start exciting the field in the visible range. It's only the lower visible range because it looks red. The sun, on the other hand is around 11,000 F. Its "white hot" because its emission peak is right in the middle of the visible range (ask the students if they think this is an "accident"—must be intelligent design!).

Slide #3 Solar Energy Radiation Spectrum

150 million kilometers away, the earth absorbs a tiny fraction of the sun's radiation. By the time the suns radiation has spread out as far as the earth, the flux has been reduced to 1370 watts/m^2, on average. The earth intercepts a fraction of this radiation.

How much does it absorb?

The earth is a disc, radius 6,400,000 meters in radius, or $\pi \times 6{,}400{,}000^2 = 1.29 \times 10^{14}$ m2 in area. So the earth is getting $1370 \times 1.29 \times 10^{14} = 1.77 \times 10^{17}$ watts. Actually it gets only 70 percent of this, as the rest is reflected (which is different from being absorbed and re-radiated). Now if the earth is in radiation equilibrium with the sun, it must be getting rid of the radiant energy at exactly this rate. The earth's surface area is $4\pi \times 6{,}400{,}000^2 = 5.15 \times 10^{14}$ m^2. So the flux of radiant energy off the earth is 0.7 x 344 watts/m^2 = 240 watts/m^2. Now from our law:

Flux = k * T^4, where k = 5.67×10^{-8} J/K^4/m^2/s, the temperature of the earth needs to be:

$$\left(\frac{240 \text{ watts/m}^2}{5.67 \times 10^{-8} \text{ watts/m}^2/\text{K}^4}\right)^{1/4} = 255 \text{ K, or about 0 F. Cold!}$$

One big thing we left out is the greenhouse effect. We need to think of three "bodies": the sun, the solid earth, and the atmosphere. All must be in self correcting thermal equilibrium. As the 255 K earth radiates, it has a maximum somewhere in the infrared spectrum. Some gases in the earth's atmosphere are not transparent to infrared radiation, notably water, CO_2, methane. So these gases absorb the radiation coming off the earth and re-radiate it back in, somewhat like a blanket.

SLIDE #4 Opacity of the Atmosphere at Different Wavelengths

But wait, don't these gases do the same thing with the radiation on the way in?

No, because remember that the frequency of solar radiation corresponds to the surface temperature of the sun, around 6000 K.

We'll look at the greenhouse effect later, but for now, we can see that it's a good thing there is some greenhouse effect, or else the average surface temperature of the earth would only be 0 F.

But what else does this flux do? For one thing, it evaporates water, and drives the hydrologic cycle.

Just how much water is this flux capable of evaporating?

It takes 40,000 Joules to evaporate a mol of water, and the molar volume of water is 18 cm^3/mol.

Lets think of how much water we can evaporate from 1 m^2 of ocean area in one year.

240 Joules/m^2/sec x 3.15 x 10^7 seconds/year = 7.56 x 10^9 Joules/m^2/year.

7.56 x 10^9 Joules/m^2/year
-------------------------------- = 189000 mols/m^2/year
40,000 Joules/mol

189000 mols/m^2/year x 18 x 10^{-6} m^3/mol = 3.4 m^3/m^2/year or 3.5 meters of ocean water/year.

That seems like a lot. I mean, how long would it take to evaporate the entire ocean at that rate?

In one year how much ocean water would we evaporate?

The surface area of the oceans is about 3.6 x 10^{14} m^2. So every year we evaporate 3.5 x 3.6 x 10^{14} m^3 = 1.26 x 10^{15} m^3. The total volume of the oceans is estimated at 1.3 x 10^{18} m^3, so

1.3 x 10^{18} m^3
----------------- = about 1,000 years.
1.26 x 10^{15} m^3

Our estimate is a little low; probably the real number is closer to 3,000 years.

But we did pretty well with our back of the envelope calculation. All we really needed was for someone to tell us the solar flux and the volume of the ocean.

So 30% or more of the volume of the oceans washes over the continents every 3,000 years. As you might guess, this is enough to cause some serious erosion, and this is how the external solar atmosphere-hydrosphere engine interacts with the mantle engine driven by radioactive decay.

Solar heating also induces currents in the atmosphere.
Explain the coriolis force and circulation patterns in the atmosphere.

SLIDE #5 Atmospheric Circulation

And also generates circulation patterns in the oceans, which are strongly influenced by the positions of the continents.

Say a few words about climate and the fine balances involved

SLIDE #6 Thermohaline circulation

SLIDE #7 North Atlantic Current

SLIDE #8 Temperatures from the Greenland Ice Sheet