Central Coast Climate Science Education

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Lesson 1: Energy Balance
And Some Fundamental Laws of Nature

(Last edit: December 6, 2012)

The entire physical world is governed by a set of immutable physical laws, discovered over the past several centuries by scientists. To be sure, they are being modified when applied to extreme circumstances. For example, Newton's laws were modified by Einstein to account for circumstances dealing with relative motions approaching the speed of light and also modified by the “quantum theory” when studying what happens at the tiny dimensions of atoms.

These basic laws apply to the Earth's climate system just as they do everywhere else in the Universe. Every aspect of the climate system and every change in the Earth's climate respond to these physical laws: ***Nothing happens simply "by chance"*****.** How the Earth's climate system evolves under these laws can be very complex, and many of the details may not be able to be forecast much in advance (see Lesson 4 on Weather and Climate).

Perhaps the most basic law of all governing the Earth's climate system is called by physicists "The First Law of Thermodynamics". But for our purposes this fancy name can simply be restated as: "Energy is neither created nor destroyed, though it can flow from one place to another and can change its form.” A shorthand name for this law is **“the conservation of energy”,** but here “conservation” doesn’t mean “turn off your TV set when you are not watching it to save energy”, it simply means energy is neither created nor destroyed, but can change from one form to another.

Before seeing how this law applies to the Earth’s climate system, we need to discuss how energy moves from one place to another. Energy flows in various forms. In this Lesson we will focus on what physicists call “electromagnetic radiation” (EMR). EMR consists of waves that all travel at the speed of light. What we call “light” is simply EMR with wavelengths in a range that our eyes (and our ordinary cameras) can detect. But if the wavelengths are much shorter than this, the EMR is what we call X-rays, and if they are much longer, they are radio waves. EMR with wavelengths a little longer than what our eyes detect is called infrared radiation (IR), and our skin detects IR as heat even though our eyes cannot see it. The motion sensors we use outside our houses sense changing amounts of infrared radiation given off by passing people--or animals!). There are a few important laws governing the flow of heat by radiation that we need to discuss.

Radiation from the surface of a solid, liquid or large amount of gas

We have described electromagnetic radiation as “waves” and for our discussion here that is a convenient description. But one of the remarkable lessons that quantum physics has taught us is that EMR can behave in some instances more like particles (called “photons”) than waves, and that is often the more appropriate way to describe it when dealing with the interaction between radiation and molecules in a gas, as in Lesson 6 on the greenhouse effect.

In either description though, the character of the radiation given off from the surface of a solid or liquid (like the ocean) or from the surface of a large amount of gas (like the sun’s surface) depends strongly on the temperature of the surface, and not much else. If the surface is very hot, as is the case for the sun's surface, then most of the energy is radiated as visible light, but in the case of cooler surfaces, like the Earth, the energy is instead radiated in the form of infrared radiation. Figure 1 illustrates this, although the range of temperatures shown only covers those for surfaces as hot as the sun and a bit cooler, but it shows two important features:

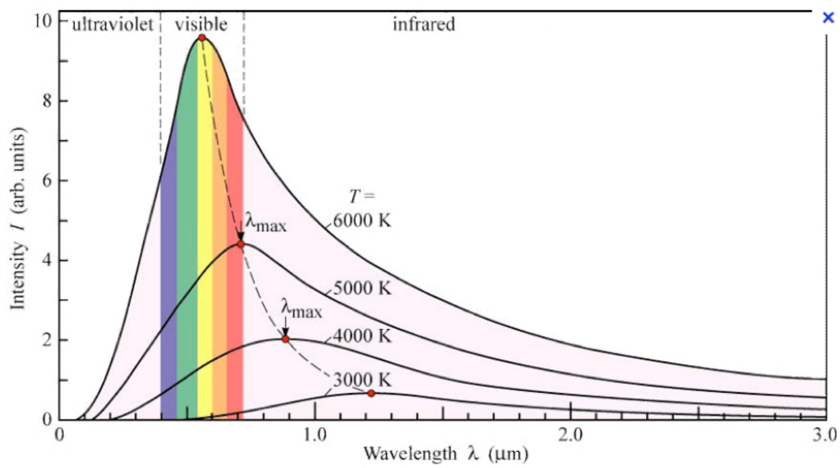

Figure 1: How the amount of radiation from surfaces of a fixed area is distributed over wavelengths depending upon the temperature of the surface.

The curve labeled T=6000K is pretty nearly the temperature of the sun’s surface.

(Digression on temperature scales: Just as we in the US use feet and miles to measure distances while most of the rest of the world uses the metric system—meters and kilometers—so there are three different temperature scales: Fahrenheit, Centigrade (or Celsius) and Kelvin. In the US we use the Fahrenheit scale (32 F = freezing water, 212 F = boiling water) while most of the rest of the world uses the centigrade or Celsius scale: 0 C = freezing water, 100 C = boiling water. Here is the formula to go from C to F: F = 1.8*C +32. So, for example,
20 degrees C is 68 F. The “K” in the figure above is a 3rd scale (the Kelvin scale) used by scientists: K = C + 273. At K = 0 (a rather chilly -459 F !), the jiggling motion of atoms in a gas slows to a halt—“absolute zero”.)

The most intense radiation from a surface about as hot as the sun is concentrated in those wavelengths (represented by the colored stripes) that our eyes sense as light. For cooler temperatures, notice two things: the most intense radiation is produced at longer wavelengths, ***and,*** the ***total*** amount of radiation emitted from a cooler surface of 3000K is much less than that from a 6000K surface of the same area—about 1/16th as much. A very important law of radiation (the “Stefan-Boltzmann” law) states that the amount of radiation given off from a given area will increase as the temperature of the surface (expressed in the Kelvin scale) raised to the 4th power.

This is a fundamental result that governs how our climate responds to an energy imbalance.

The temperature of the Earth's surface varies a lot from the poles to the tropics of course, but the average value is about 59F = 15 C = 288 K. Most of the radiation from the Earth's surface occurs at very much longer wavelengths (called "far infrared wavelengths") than the radiant energy we get from the sun.

Now we can apply the basic law of "conservation of energy" to the Earth's climate system. Imagine a large imaginary sphere surrounding the Earth, well above the Earth's atmosphere. In fact, one can consider that it is on the surface of this imaginary sphere that the numerous NASA satellites devoted to studying Earth's climate, as well as those from other nations, are orbiting. Figure 2 (where we have drawn a flat Earth instead of our round globe!) shows several parts of the Earth's climate system and the arrows represent the flow of energy between them.

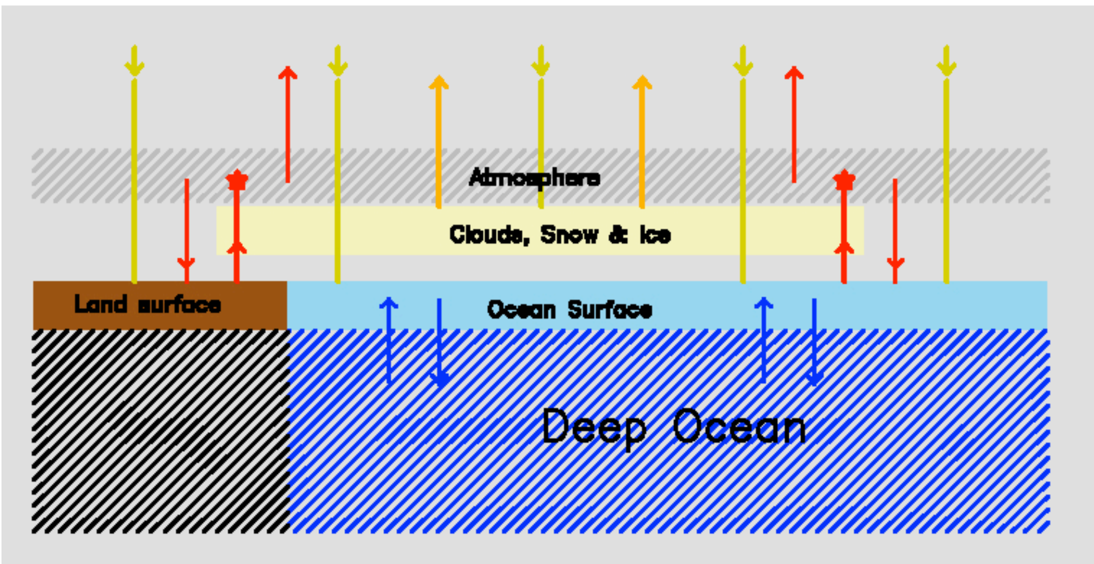

Figure 2

Except for a negligible amount of energy flowing up from the Earth's interior due to radioactive decay, all the energy flowing towards the surface of the Earth's land and ocean comes from the Sun, mostly in the form of visible light. This inflow of energy from the Sun is represented by the downward yellow arrows. Some of this energy is reflected back into space, especially by bright surfaces like clouds, snow, ice, and sandy deserts, but also by haze, both natural and man made, all represented by the pale yellow bar labeled "Clouds, Snow & Ice". This reflected sunlight is represented by the upward orangish arrows. The fraction of the incoming sunlight that is *not* reflected back into space (about 70%) warms the surface of the Earth, both land and sea.

The warm surface of the Earth (whose, average temperature is about 59 F) sends infrared radiation headed back out into space. This is represented by two wide upward red arrows, one originating from the top layers of the land (the short brown bar), and the other from the ocean's surface layers, represented by the light blue bar.

Not all of this infrared radiation escapes directly into space, however. Some molecules have a voracious "appetite" for absorbing and then re-emitting infrared radiation, the two most important in the Earth's atmosphere being water vapor (H_2O) and carbon dioxide (CO_2), but there are several others as well. The upper gray cross-hatched bar represents the Earth's atmosphere and the two red "stars" indicate where CO_2 molecules have intercepted some of this radiation.
This intercepted radiation is re-emitted. Some of this re-emitted infrared energy is directed back towards the Earth's surface, where it is absorbed and further warms the Earth's surface. This extra warming is the famous "Greenhouse effect" which will be discussed in more detail in Lesson 3. Some of the infrared radiation does eventually work its way out into space and this is represented by the topmost upward red arrows.

The blue arrows show the exchange of energy between the shallow and deeper layers of the ocean, not by radiation but by the circulation of water with different temperatures. In Lesson 5 we will talk about the large blue lower crosshatched area (the deep ocean) as well as the significance of these blue arrows representing the exchange of energy between the ocean surface layers and the deeper ocean.

If the diagram of Figure 1 represented your savings account and you wanted to know whether you would have anything left over to add to your savings account at the end of the year (or whether you had to withdraw some!) you would start with your gross income (the incoming sunlight) then subtract "right off the top" the loss due to taxes (the reflected sunlight) and then further subtract off your net expenses (the escaping upward red arrows). If we pushed the analogy a little further we might say that the downward red arrows were rebates on our purchases, but no analogy is perfect!

So, from the point of view of the satellites orbiting well above the Earth's atmosphere, if we want to ask the question: Is the Earth gaining or losing energy or is it in approximate energy balance "all we have to do" is ask the satellites to measure the incoming solar radiation, subtract off the reflected sunlight and in addition subtract off the escaping infrared radiation and see if there is an energy imbalance. If, averaged over a few decades, there is an energy imbalance, then the Earth's surface will either heat up or cool down and the ***climate will change***. ***This is the inescapable result of the First Law of Thermodynamics.*** It turns out that these are not an easy set of measurements to make, but, as we will discuss in Lesson 5, ***there is very strong evidence that probably for at least a century, and especially for the past several decades, the Earth is not in energy balance, and in fact is gaining energy.***

Before we discuss that, we need to explore three important concepts--"Forcings and Feedbacks"--which is the topic of Lesson 2, and then discuss in more detail the greenhouse effect, which we do in Lesson 3. In Lesson 4 we emphasize the important distinction between “weather” and “climate” and briefly discuss the computer simulations describing the Earth's climate.