



Central Coast Climate Science Education
Dr. Ray Weymann ray.climate@charter.net

Lesson 3: The Greenhouse Effect

Last edit: December 7, 2012

The “greenhouse effect” is an observed and well-understood fact, not a speculation or an hypothesis. While the consequences of increasing CO₂ and other greenhouse gases are a matter of concern, we owe our existence to it: Without the greenhouse effect -- the trapping of infrared heat from water vapor and CO₂ and other greenhouse gases -- the Earth's temperature would be way below freezing: about zero degrees Fahrenheit.

The laws of physics governing the passage of radiation through gases in the Earth's atmosphere that absorb some of the radiation, apply to the outer layers of stars as well as the other planets in our solar system. Calculations that predict the amount of radiation that escapes into space, depending upon the wavelength of the radiation, are in excellent agreement with what is observed.

Although this trapping of radiation is called the greenhouse effect, it actually operates in a little different way from the hot houses where we can grow tomatoes in winter.

In Lesson 1, we noted that electromagnetic radiation can be thought of under some circumstances as waves, but in other circumstances it is more convenient to think of radiation as traveling in little particles of pure energy called “photons”. This does not mean physicists are unsure of how electromagnetic radiation really behaves. Quantum physics gives an exact description of this radiation and how it interacts with atoms and molecules and has been experimentally verified to extremely high accuracy. Quantum physics teaches us that energy carried by each of these photons depends upon the wavelength of the radiation when it is thought of as a wave: the shorter the wavelength of the radiation (or equivalently, the higher the frequency of the radiation), the more each photon carries. Additionally, quantum physics teaches us that atoms and molecules can only absorb or emits these photons if the photons are carrying very definite specific amounts of energy. We can see this in concept in action in Figure 1.

Figure 1 below is what astronomers call a "spectrum", in this case a spectrum of our Sun. The various wavelengths of light (which our eyes sense as the colors of the rainbow) are spread out in the way droplets spread out the light from the Sun into a rainbow.

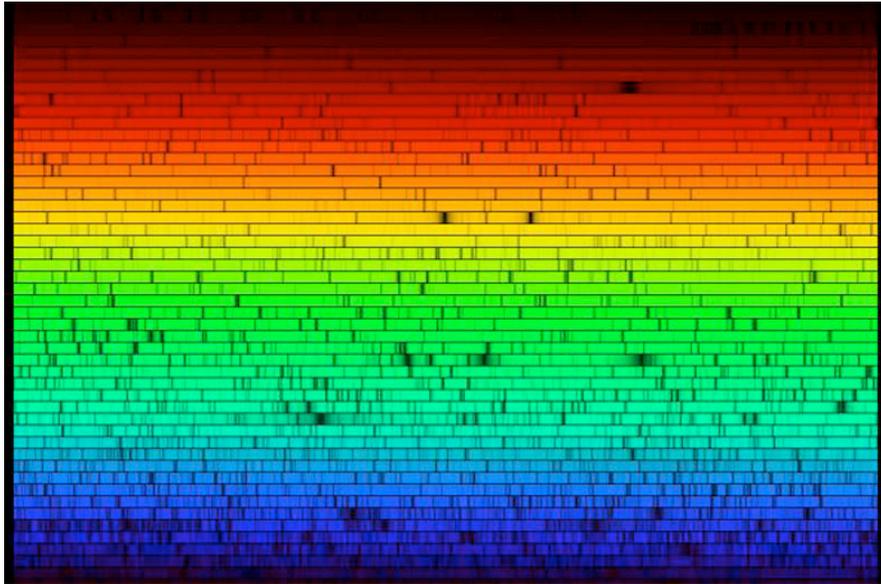


Figure 1: A spectrum of the Sun

(In Figure 1, the format has been arranged so that instead of one long continuous band of light ranging from red to deep blue, smaller segments of the spectrum have been 'wrapped around' so the spectrum can fit in a rectangular format.)

The dark regions are regions where specific kinds of atoms absorb photons with just the right amount of energy that quantum physics allows for that particular kind of atom or molecule. This inhibits the light at those wavelengths from escaping. For example, the two dark bands in the middle of the yellowish-orange region in Figure 1 are due to sodium atoms. Even though only about 1 in every million atoms in the Sun is a sodium atom, they are still very effective in blocking light at specific wavelengths.

Figure 2 below is a calculated spectrum¹ using the same techniques that astronomers use for calculating the appearance of the Sun's spectrum, but for the atmospheric composition of the Earth. It shows the amount of energy at each infrared wavelength emitted from the Earth's surface (blue line) and the red line shows the amount actually escaping into space. These agree very well with observations made from satellites. Figure 2 illustrates the trapping of infrared radiation by both water vapor and carbon dioxide. In Figure 2, "F(SRF)", the blue line, refers to the amount of infrared energy emitted from the Earth's surface (recall Figure 1 of Lesson 1). The red line marked "F(TOA)", is the amount of energy measured at "TOA"---the top of the atmosphere---that actually escapes to outer space. The rest is returned to the Earth's surface, altering the Earth's energy balance over what it would have been in the absence of these absorbing gases, as explained in Lesson 1.

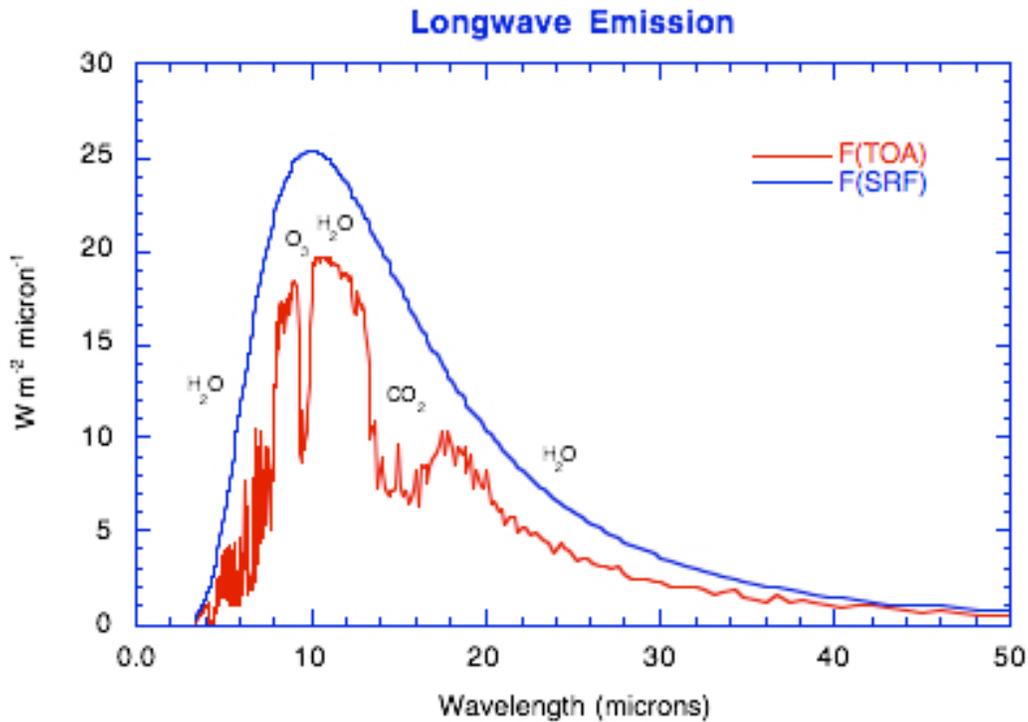


Figure 2

A further vivid example of the greenhouse effect is provided by a comparison of three of the inner planets of our solar system: Venus, Earth, and Mars.

In Table 1 below, the first column of numbers shows what the approximate temperature would be in the absence of any atmosphere.² The 2nd column of numbers shows the approximate actual **observed** surface temperature. Obviously Venus is *much* hotter than it would be without its thick atmosphere, mostly carbon dioxide -- this is due to an extreme greenhouse effect. The Earth is only moderately warmer than expected due to its moderate greenhouse effect. Mars, on the other hand, with its very thin atmosphere, shows only a slight greenhouse effect³

Planet	Temp(F):No GHG	Temp(F): Actual
Venus	79	880
Earth	-2	58
Mars	-88	-81

Table 1

Water Vapor: Is it or Isn't it a Greenhouse Gas?

In the sense of trapping outgoing infrared radiation -- absolutely. In the sense of humans directly adding water vapor to the atmosphere (except very locally) and thus affecting climate: No. The reason is that it rains and snows water, but it never snows or rains carbon dioxide. The amount of water vapor that the atmosphere can hold is governed by the temperature -- if we were somehow to magically inject huge amounts of water vapor into the atmosphere while keeping the temperature constant, it would quickly come down as rain or snow. As

explained in [Lesson 2, “Forcings” and “Feedbacks”](#), however, water vapor acts as a positive feedback, enhancing the effect of any warming forcing process.

On the other hand, as we inject carbon dioxide into the atmosphere (not magically, but by the burning of fossil fuels and deforestation) about half this injected CO₂ accumulates in the atmosphere while (currently) about 50% is reabsorbed by the biosphere (e.g. vegetation) and the ocean.

Thus, in the same way that the delicate energy balance of the Earth's climate system is being altered, as will be discussed in Lesson 5, "Is the Earth In Energy Balance?", so the delicate balance of the Carbon Cycle is being altered by human activity. Lesson 6 discusses the carbon cycle and the extent to which the climate system is out of 'carbon balance'.

The buildup of the amount of CO₂ in the atmosphere has been directly measured since the mid-1950s and the graph depicting this buildup is the famous "Keeling Curve", shown in Figure 3 below.

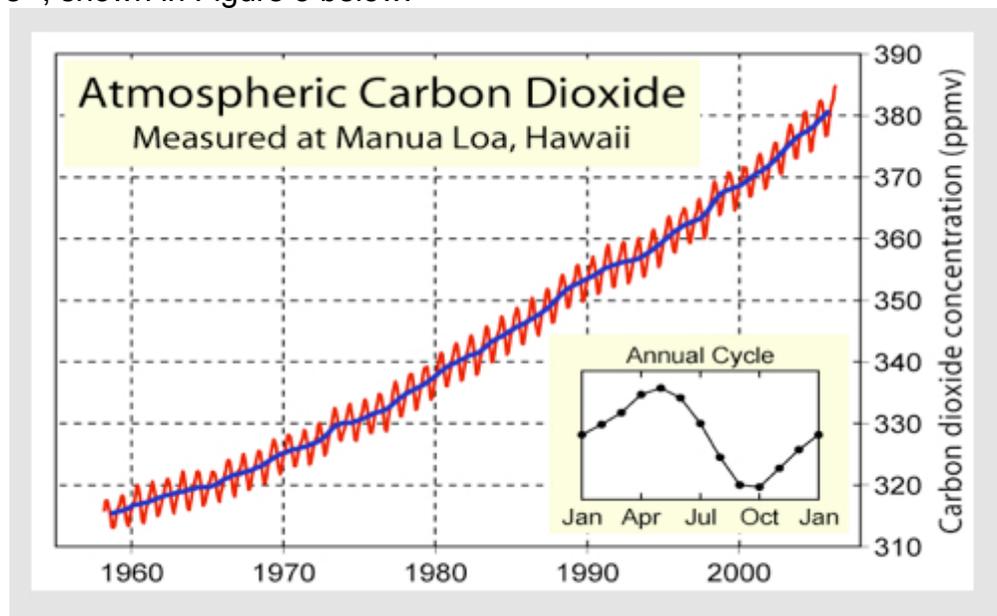


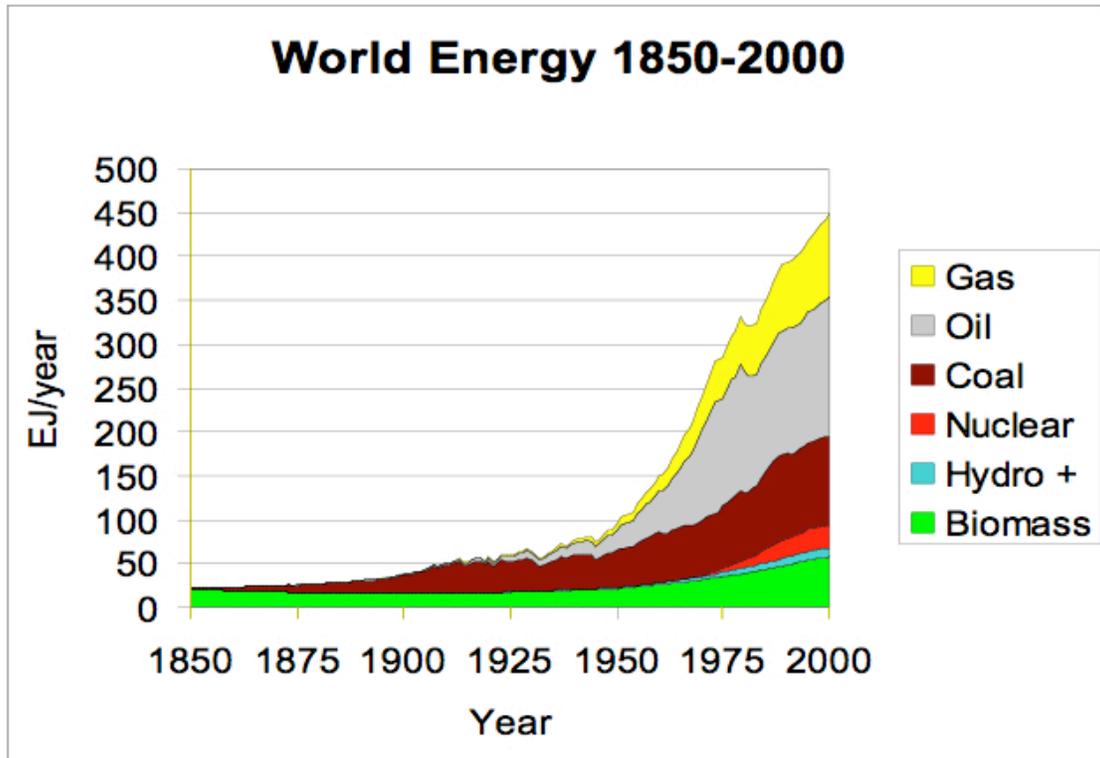
Figure 3: Keeling Curve

Prior to these measurements, the amount of CO₂ in the atmosphere can be measured indirectly (as we will discuss further in Lesson 7 in connection with the Ice Ages), and reveals that prior to the Industrial Revolution the CO₂ amount stood at about 280 ppm, but has been building at an accelerating rate as the world's population and economy grows.

What Has Caused the Increase in CO₂?

Can we be sure that this increase is entirely due to human activities? Yes, on two grounds: First, as Figure 4 below shows, the growth in energy usage over this period, (largely based on the burning of fossil fuels which release CO₂) mirrors the increase in CO₂. Volcanic emission of CO₂ has no measurable effect on the amount that has been accumulating over the last several decades, otherwise

there would be a significant spike in the Keeling Curve following a major eruption (for example, Mt. Pinatubo in 1991).



Fossil fuels drove most of the growth & were almost 80% of supply in 2000.

Figure 4

Secondly, there is direct physical proof that this increase is essentially entirely based upon fossil fuel combustion. It is based upon the analysis of the isotopes of carbon. Isotopes are forms of a chemical element, that have identical chemical properties, but differ in weight due to differing numbers of neutrons in the atom's nucleus.

For example, "carbon 14" differs from the more common other two isotopes of carbon, "carbon 12" (99% of all carbon) and "carbon 13" in having 8 neutrons, compared to 6 and 7 for the other two, respectively. But, it is also radioactive and an individual carbon 14 atom decays after a few thousand years. Carbon 14 atoms in the atmosphere are continuously replenished by nuclear reactions resulting from bombardment of the atmosphere by cosmic rays. But, the coal, oil and natural gas formed many millions of years ago and buried deep underground are shielded from these cosmic rays and so contain no carbon 14. When burned, therefore, the resulting carbon dioxide is depleted in carbon 14, and thus dilutes the amount of carbon 14 isotope in the measured carbon dioxide. But this isotope was also produced in significant quantities in the atmosphere when above-ground nuclear explosions took place and so it is no longer a useful measure of the contribution of fossil fuel burning to the amount of CO₂ in the atmosphere.

But there is also strong evidence from the carbon 12 and carbon 13 isotope ratios in the atmospheric carbon dioxide but they are subtler, and do not involve radioactivity. See for example: <http://www.skepticalscience.com/CO2-emissions-correlation-with-CO2-concentration.htm>

With the background in Lessons 1, 2, and 3, we will turn in Lesson 5 to evidence bearing on whether the Earth is currently in energy balance, and if not, why not. But, before that, we devote one more lesson, **Lesson 4, "Weather, Climate and Computability"**, to removing common confusion between *weather* and *climate*.

¹ Taken from a paper by Keith and Trenbeth, published in 1997 in the Bulletin of the American Meteorological Association.

² We assume an albedo in this case of 0.3: For an ice covered earth it would be higher and the temperature even lower.

³ Although Mars has more CO₂ above each square inch of its surface than does earth, because of the very low atmospheric pressure, the CO₂ molecules are not "jostled" by nearby molecules as they are on earth ("pressure broadening"). Consequently on Mars they absorb energy over only very small regions of the spectrum. I thank Prof. John Keller for pointing this out to me.