

This talk was originally prepared by Laura Foster Voss for a Bowdoin College Parents' weekend public lecture in October 2008. It has been modified slightly since then but remains the same in spirit. Feel free to use it. Please make sure to credit sources of information and images.



In the fall of 2007, AI Gore and the Intergovernmental Panel on Climate Change (IPCC) were jointly awarded the Nobel Peace Prize for their work to disseminate information about the science causing and the predicted effects of global climate change. The IPCC is a United Nations organization of international scholars. The panel's purpose is to provide assessment of the causes and risks of anthropogenic (human caused) climate change.



The 2007 Synthesis Report summarizes the causes and predicted outcomes of climate change on society and ecosystems. This very readable document is recommended for further background and understanding and is the source of images labeled "IPCC AR4".



Most scientists agree that data such as the rise in ocean temperature and sea level and the decrease in Northern Hemisphere snow cover are clear indication of unequivocal human impact driving global warming.



This photographic evidence is just one example used to illustrate changes in climate. This is a very important example. Many communities near glaciers depend on these giant ice formations for fresh water. As the glaciers melt permanently, this source of water is stopped.



To understand global warming, we have to understand the balance of the radiative budget. The difference in the amount of heat coming into our system and the amount of heat leaving our system. The system is the earth and the surrounding atmosphere. The source of our incoming energy is the sun and is represented by the 342 W/m<sup>2</sup> of incoming power or 342 J of energy per second per square meter, represented by the arrows directed down. The left side of the image above accounts for what happens to this energy. Some is reflected by clouds and aerosols (called the albedo of the atmosphere). Some is directly absorbed by the atmosphere. Much is absorbed by the surface of the earth. There is also energy leaving the system, outgoing terrestrial radiation. The right side of this image accounts for the fate of the energy ( $390 \text{ J/(s} \cdot \text{m}^2$ ) of surface radiation. To understand the  $324 \text{ W/m}^2$  of back radiation attributed to greenhouse gases, we must think about the actual energy of the surface radiation and the molecular structure of the gases.



To think about the energy of incoming solar radiation and outgoing terrestrial radiation, we can model both the sun and the earth as blackbody radiators. Understanding the precise meaning of "blackbody radiator" requires more physics and quantum mechanics than will be discussed here. The image above is taken from an undergraduate chemistry textbook with a detailed explanation of the origin and explanation of blackbody radiation, the so-called UV catastrophe, and how Max Planck developed the idea of energy quantization in explaining blackbody radiation. All we need to understand is that a blackbody radiator will emit a spectrum of light that depends on its temperature. The higher the temperature, the shorter the wavelength of light emitted. Also, the higher the temperature, the more narrow the spectrum, or number of wavelengths, of light emitted. The figure above demonstrates the calculated blackbody radiation curves of energy as a function of wavelength for the sun and the earth. Since the temperature of the sun is around 6000 K and the temperature of the earth is around 300 K, the curve for the sun is peaked at a much shorter wavelength than that of the earth. The peak of incoming solar radiation is approximately 550 nanometers (nm), which corresponds to what we call the visible light. We humans evolved on this earth with this light as our illumination source. Our eyes have evolved such that they are very sensitive detectors of visible light. Outgoing terrestrial radiation has a much longer wavelength and is in the infrared region of the electromagnetic spectrum, peaking around 15,000 nm or 15 micrometers (µm). What we need to understand to understand man's impact on global temperatures is how we are affecting the energy balance, changing the amount of light coming into our system or leaving our system. We call this changes in radiative forcing. The chief way we have made changes to this energy balance is through changing the composition of our atmosphere and by altering the surface of our earth (land use).



The image above, from the IPCC's Third Assessment Report, plots the change in radiative forcing for different atmospheric constituents as a function of our level of scientific understanding for each constituent. The image is plotting differences in forcing in 1750 (before the industrial revolution) to the year 2000. "Solar" indicates the changes in incoming solar radiation. The industrial revolution marks the beginning of anthropogenic altering of the atmosphere through the combustion of large quantities of fossil fuels.



Clearly, the largest and most understood anthropogenic impact is the introduction of the "greenhouse gases" into the atmosphere. To understand this impact, we must understand what is meant by a "greenhouse gas".

Composition of Dry Air at Sea Level	
Gas	Composition (% by Volume)
$N_2$	78.03
$O_2$	20.99
Ar	0.94
$CO_2$	0.038815 *
Ne	0.0015
He	0.000524
Kr	0.00014
Xe	0.000006

Our atmosphere is approximately 78% nitrogen, 21% oxygen, and 1% argon. There are many other trace gases in the mix. The amount of water is not reported because it varies from 4% in the tropics to 0.00001% at the South Pole. We will consider water vapor and global warming later. The amount of  $CO_2$  continues to increase as we continue to burn fossil fuels. See the link above for the latest monthly average of measured  $CO_2$  in Mauna Loa, Hawaii. Note: When the Chang text was published the value reported as 0.033% or 330 parts per million (ppm).

Composition of Dry Air at Sea Level		
Gas	Composition (% by Volume)	
$N_2$	78.03	
$O_2$	20.99	
Ar	0.94	
$CO_2$	0.038815	
Ne	0.0015	
He	0.000524	
Kr	0.00014	
Xe	0.000006	

Nitrogen and oxygen are homonuclear diatomic gases. This simply means that the molecules are two atoms of the same species that share a bond. The electrons in this molecule are shared evenly by both atoms, resulting in purely covalent bonds with no dipole moment.

Compo at Sea	osition of Dry Air Level	
N <sub>2</sub> Gas	Composition (% by Volume)	
N <sub>2</sub>	78.03	
<b>O</b> <sub>2</sub>	20.99	
Ar	0.94	
CO <sub>2</sub>	0.038815	CO.
Ne	0.0015	
Не	0.000524	
Kr	0.00014	
Xe	0.000006	

Carbon dioxide is a heteronuclear triatomic molecule. The atoms in this gas are not all the same. The atoms in the carbon dioxide do not share their electrons evenly, resulting in polar covalent bonds that have a dipole moment. Quantum mechanics tells us and experiments prove that bonds with no dipole moment do not absorb infrared radiation while bonds with a dipole moment do.



 $N_2$  and  $O_2$  will not absorb infrared light.  $CO_2$ ,  $H_2O$ , methane ( $CH_4$ ), and halocarbons like Freon ( $CF_3CI$ ) all have polar bonds and can absorb infrared light.



The image above is the infrared absorbance spectrum of  $CO_2$  plotting the absorbance as a function of wavelength in microns (micrometers,  $\mu$ m; 1  $\mu$ m = 1000 nm). We see that the  $CO_2$  absorbs the light at specific wavelengths. These wavelengths correspond to different molecular vibrations in  $CO_2$ . Infrared spectra can be found online at the NIST Chemistry Webbook (http://webbook.nist.gov/ chemistry/).



These are examples of molecular vibrations that result when  $CO_2$  absorbs infrared radiation. Note: The symmetric stretch is not infrared active, but this is beyond the scope of this talk. These images are simply given to demonstrate what is meant by "molecular vibrations".



We see that water is infrared active with a spectrum different than  $\mbox{CO}_2$ 



Methane is also infrared active as are CFCs (not shown, but see NIST Chemistry Webbook for infrared spectra of CFCs)



The data presented in the absorbance spectrum was generated an infrared spectrometer. Our sample of  $CO_2$  is placed between our infrared source (blackbody radiator) and our detector (eyeball). Any energy that is absorbed will not be detected and we can plot that absorbance as a function of wavelength. The Beer-Lambert law tells us that the absorbance (A) is equal to the concentration of the sample (c) times the length of the path in which the sample is contained (I) times a wavelength-dependent and molecule dependent physical constant called the molar absorptivity ( $\epsilon$ ). As long as our species does not change and our path length does not change, then we can understand the change in absorbance as a function of changing concentration.



Putting these ideas together and remembering that the outgoing terrestrial radiation is peaked around 15  $\mu m$ . We can see that we are doing an infrared experiment in our atmosphere where we are increasing the amount of outgoing terrestrial radiation being contained by increasing the concentration of CO<sub>2</sub> in the atmosphere.



We see that there is a broad peak in the absorbance around 15 micrometers.



This peak corresponds closely to the peak of the outgoing terrestrial radiation. Thus,  $CO_2$  ability to absorb infrared light. These gases are all called "greenhouse gases" because, like the roof of a greenhouse, the allow energy from the sun to pass in without being attenuated but absorb the outgoing energy and, thereby, heat up the system.



The image above gives percent composition by species of the major greenhouse gases that occur naturally and are generated by human activity. Not included are ozone and, more importantly, water. Water is not included for two reasons. As mentioned before the composition of water in the atmosphere varies greatly from region to region. Also, the amount of water in the atmosphere has not changed greatly due to anthropogenic activity. It is very important to note, however, that as global temperatures rise we will see a rise in water vapor, which will trap more infrared radiation and increase in global temperatures. This is called a positive feedback. With more water vapor, we may also see more clouds which would lead to more reflection of incoming solar radiation (albedo effect) and to global cooling. This is called a negative feedback. The role that water vapor plays in the radiative budget is still being investigated and debated.



Carbon dioxide is the most significant greenhouse gas. We can attribute its production to the human activities depicted in the chart above.



To understand how the human activities produce carbon dioxide, we look at combustion. Above is the balanced chemical equation for the complete combustion of methane in the presence of oxygen to form carbon dioxide and water. This chemical reaction also produces energy, specifically 890 kilojoules for every mole burned.

Substance	Formula	$\Delta H^{\circ}$
benzene	C_H_(1)	-3268
carbon	C(s, graphite)	-394
ethanol	$C_{2}H_{2}OH(l)$	-1368
ethyne (acetylene)	$C_2H_2(g)$	-1300
glucose	$C_{\epsilon}H_{12}O_{\epsilon}(s)$	-2808
hydrogen	$H_2(g)$	-286
methane	$CH_4(g)$	-890
octane	$C_8H_{18}(l)$	-5471
propane	$C_3H_8(g)$	-2220
urea	$O(NH_2)_2(s)$	-632

In fact, combustion of hydrocarbons is how humans fuel their existence from burning gasoline (approximated as octane, 5471 kJ/mol) in cars, propane (2220 kJ/mol) in stoves and heaters, and food (approximated as glucose, 2808 kJ/mol) in our bodies. Burning all of these fuels, as well as others like ethanol and coal and wood, produces  $CO_2$ .



We can see the evidence of increased CO<sub>2</sub> levels from the burning of fuels in the Mauna Loa record. Note: Go to http://www.esrl.noaa.gov/gmd/ccgg/trends/ #mlo\_full to get the latest updated image including last month's average.



We can see that as the  $CO_2$  concentration has increased, the global mean temperature has also increased. We would predict this knowing what we know understand about how  $CO_2$  traps energy that would otherwise leave our system and, thereby, increases the temperature of our system.



I have chosen the consumption of bottled water to illustrate the amount of CO<sub>2</sub> produced due to one specific human activity. This is often referred to as the carbon footprint of an activity. I got some of my numbers for this argument from Pablo Päster's article that can be found here: http://www.salon.com/life/feature/ 2008/01/14/ask\_pablo\_water/index.html

It takes 6.5 kilograms of oil to produce one 1000 grams of PET, using 294 kilograms of water and producing 3700 grams of carbon dioxide.

It takes 6.5 kilograms of oil to produce one 1000 grams of PET, using 294 kilograms of water and producing 3700 grams of carbon dioxide.

Shipping water also consumes fuel and results in carbon dioxide emissions. These emissions can be expressed in units of grams per ton per kilometer.

It takes 6.5 kilograms of oil to produce one 1000 grams of PET, using 294 kilograms of water and producing 3700 grams of carbon dioxide.

Shipping water also consumes fuel and results in carbon dioxide emissions. These emissions can be expressed in units of grams per ton per kilometer.

container ship:	17 g/(ton·km)	
train:	56 g/(ton·km)	
truck:	102 g/(ton∙km)	s
jet:	570 g/(ton∙km)	S



This calculation only considers production of the bottle and transportation and does not include any energy cost of actually bottling the water. There are additional environmental problems like depletion of local water sources at the bottling site and health risks associated with drinking bottled water that are also not considered in this argument.



44 g  $CO_2$  per mole is simply the molecular weight of  $CO_2$ 

1 mole of ideal gas occupies 22.4 L at 1 atmosphere and room temperature. This is a reasonable approximation for  $CO_2$  as well.



We are ignoring the weight of the bottle.

The density of water is approximated as 1 gram per milliliter. This is a reasonable approximation.

44 g CO<sub>2</sub> per mole is simply the molecular weight of CO<sub>2</sub>

1 mole of ideal gas occupies 22.4 L at 1 atmosphere and room temperature. This is a reasonable approximation for  $CO_2$  as well.







I have a 16" diameter Earth Ball that I use as a demonstration. This is basically a beach ball. They can be found here http://www.earthball.com/ and in many toy stores and museum gift shops.







