Additional Reading

Introduction

In the fall of 2007, Al Gore and the Intergovernmental Panel on Climate Change (IPCC) were jointly awarded the Nobel Peace Prize for their work to disseminate information about the causes of, the predicted effects of, and measures needed to counteract global climate change. The IPCC is a United Nations organization of international scholars whose purpose is to provide assessment of the causes and risks of anthropogenic (human-caused) climate change. Their 2007 Synthesis Report summarizes the causes and predicted outcomes of climate change on society and ecosystems. The report details the growing consensus among scientists that data showing increases in ocean temperature and sea level and a decrease in snow cover provide clear indication of global warming, as demonstrated in the data presented in Figure 1. The conclusion that our Earth is warming is supported by much more numerical and scientifically measured data. However, a pictorial example may prove to be more convincing and demonstrative. The pictures in Figure 2 show the decrease in the size of the Boulder Glacier in Glacier National Park between 1932 and 1988. This is not only a great visual example but is also a very important example demonstrating the impact of global warming on human existence. Communities living near such glaciers depend on these icy giants as sources of fresh water. As the glaciers melt permanently, these sources of fresh water disappear, threatening the survival of these communities.

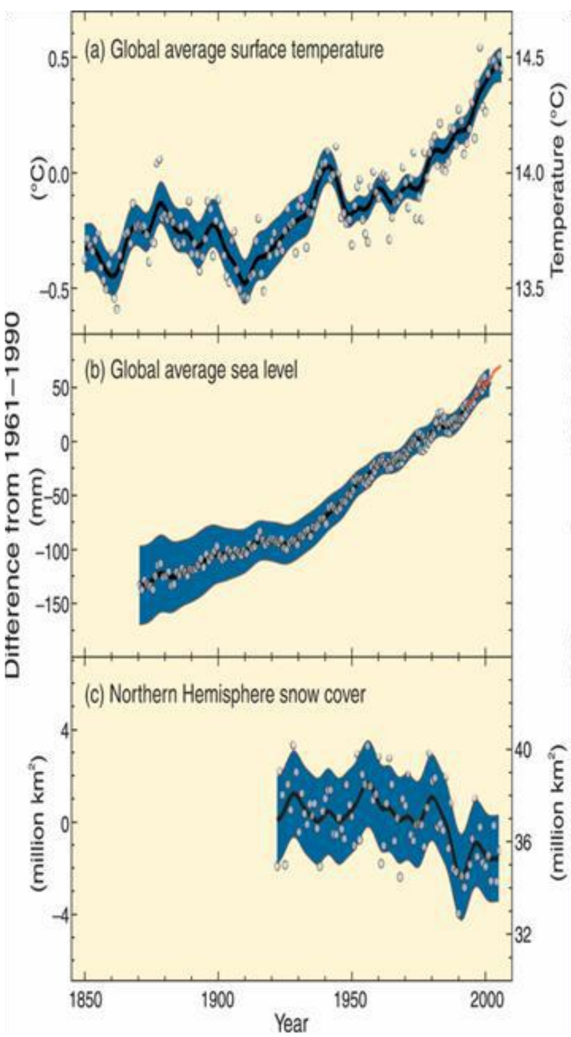

Figure 1. Data demonstrating the difference in (a) Earth's average surface temperature, (b) the average global sea level, and (c) the amount of snow cover in the Northern Hemisphere. The differences are relative to averages for the period from 1961 to 1990. Source: IPCC AR4.

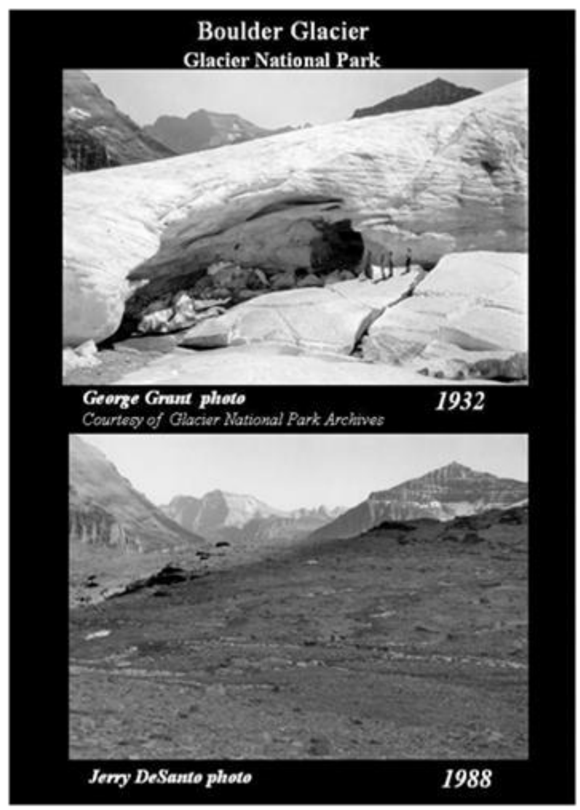

Figure 2. Photos depict Boulder Glacier in Glacier National Park in 1932 and 1988. Source: Glacier National Park Archives.

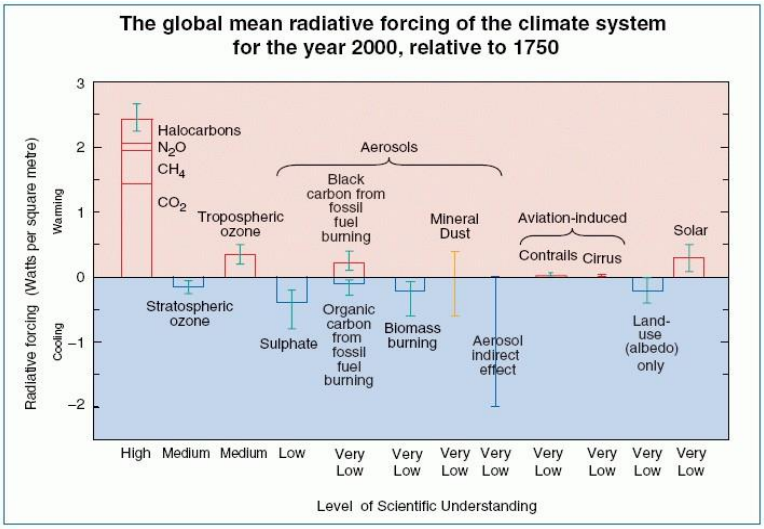

Figure 3. Difference in mean radiative forcing for different constituents that contribute to changes in global temperature plotted as a function of the level of our scientific understanding for each constituent. Note that the first column on the right represents global warming due to greenhouse gas emissions.

To better understand the link between human activity and climate, consider the diagram in Figure 3. This graph plots the mean radiative forcing, which is simply the average global warming potential, of different constituents on an x-axis that indicates our level of scientific knowledge about the constituent. The y-axis can be read as the difference in the radiative forcing value for the specific constituent between the years 2000 and 1750. Any value above the x-axis indicates that the constituent contributes to global warming; any value below the x-axis indicates that the constituent contributes to global cooling. The contributions from constituents that cause warming greatly outweigh the contributions that would cause cooling; therefore, we see a warming trend. Understanding all the constituents and their effects is well beyond the scope of this lesson and would take an in-depth exploration into atmospheric chemistry and physics to begin to understand. Note that many of the constituents are labeled “very low” for their level of scientific understanding. This means that even climate scientists do not fully understand the full effect on global temperature that these constituents have. These are areas of on-going scientific research.

An initial question may arise from the title. What is significant about the year 1750? You may remember from your history classes that the Industrial Revolution began in the mid-eighteenth century. This boom in technological advancement marks the beginning of widespread use of burning fossil fuels to produce energy. Since this time, the resulting gas and particle by-products of burning fossil fuels have released into the atmosphere, thus altering the composition of the air. The constituents represented by columns 1, 3, 4, and 5 of Figure 3 are all attributed to the fossil fuel combustion.

In this module, we will focus our attention on the contributor where there is a high level of scientific understanding about change in radiative forcing. The first column on the x-axis represents the change in radiative forcing due to the increase of greenhouse gases in the atmosphere. The different segments of the bar represent the greenhouse gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons (primarily man-made molecules used as refrigerants and propellants such as Freon-12 (CF_2Cl_2)). A greenhouse gas works like the glass in a greenhouse: it allows the sunlight to enter the system but does not allow the heat to escape. While many of these gases occur naturally, their levels have risen dramatically since the 18th century due to human activity. Their impact on global temperature can be understood by explaining some atmospheric chemistry and basic molecular properties of gases.

Science behind greenhouse gasses

Earth’s atmosphere is primarily nitrogen (N_2: 78%) and oxygen (O_2: 21%) and argon (Ar: 1%) with trace levels of many other gases, including the ones mentioned above. For instance, CO_2 currently accounts for about 0.0392% of the atmosphere. It is important to note that water is also a greenhouse gas; however, the amount of water in the atmosphere has not changed significantly since the Industrial

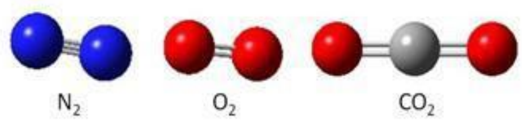

Figure 4. Figure 4. Molecular structure of nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2).

Revolution. The presence of nitrogen, oxygen, and argon do not significantly affect the temperature of our atmosphere, while CO_2 does. Or put differently N_2, O_2, and Ar are not greenhouse gases, while CO_2 is. The molecular structures of the different gases help explain why this is true. Figure 4 shows the molecular structures for N_2, O_2, and CO_2. N_2 and O_2 have hemolytic bonds, meaning the bonds join to atoms of the same species: CO_2 has heterolytic bonds that join atoms of different species. Quantum mechanics tells us that only heterolytic bonds are infrared active. Or more simply put, bonds between unlike atoms are capable of absorbing infrared light. Therefore, CO_2 will absorb some wavelengths of infrared light while N_2 and O_2 will not. The ability to absorb infrared light is the molecular property that makes the constituents in the column furthest to the left in Figure 3 greenhouse gases. All are made of different kinds of molecules and, therefore, have heterolytic bonds: all will absorb infrared light.

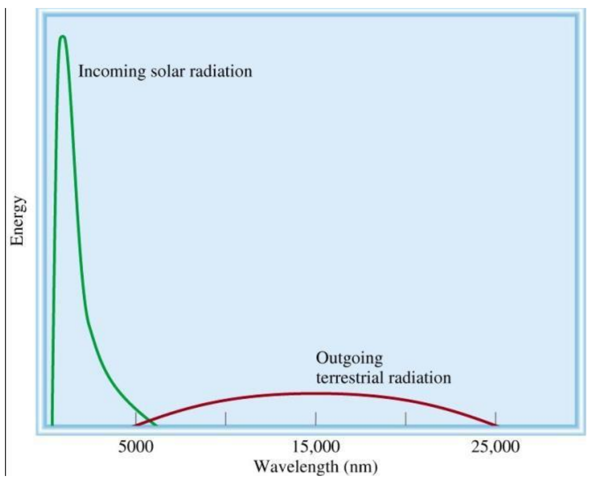

Figure 5. Incoming solar radiation and outgoing terrestrial radiation plotted as a function of energy versus wavelength. Source: *Chemistry*, 9th Edition by Raymond Chang, McGraw Hill, 2007.

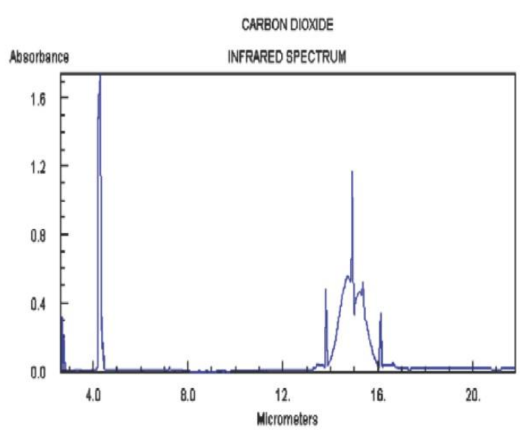

Figure 6. Infrared spectrum of carbon dioxide (CO_2) plotted as absorbance versus wavelength. Where there are peaks in the spectrum, the gas is absorbing the energy of the light. Source: Data compilation copyright by the U.S. Secretary of Commerce on behalf of the U.S.A. Data compiled by: Coblentz Society, Inc.

But why is this important? To understand the answer, we have to consider the energy balance of our Earth, namely the incoming energy and the outgoing energy. Figure 5 is a gross oversimplification of the energy balance of the earth. It shows the incoming solar radiation (light coming from the sun to Earth) and outgoing terrestrial radiation (light leaving Earth into space). The y-axis represents the energy while the x-axis represents the wavelength of the light in nanometers (nm). What we can see is that the incoming solar radiation is made up of much shorter wavelengths of light than the outgoing terrestrial radiation. The incoming solar radiation is primarily visible light. Infrared light is another form of electromagnetic radiation that has longer wavelength and, therefore, lower energy than visible light. Outgoing terrestrial radiation is infrared light. The energy of the electromagnetic radiation determines how molecules interact with waves. For the most part, visible light passes through atmospheric gases without interacting with the molecules. This is why air is basically transparent to the visible light our eyes can detect. Our atmosphere allows visible incoming solar radiation to come in without being greatly altered. Infrared light, however, will interact with molecules possessing heterolytic bonds. Depending on the specific bond, certain wavelengths will be absorbed and cause the atoms in the bond to vibrate. The absorption of infrared light by CO_2 is demonstrated in Figure 6. This infrared spectrum shows the amount of absorbance per wavelength when infrared light is passed through a sample of CO_2 gas. The x-axis represents wavelength in micrometers (μm), where 1 μm = 1000 nm. We can see that there is a broad absorption peak centered at approximately 15 μm or 15000 nm. If we compare this to the spectrum of outgoing terrestrial radiation in Figure 5, we see that this absorption band coincides with the peak of the outgoing terrestrial radiation. This means that CO_2 in the atmosphere can absorb outgoing terrestrial radiation, thereby trapping that energy in our atmosphere. This warms the atmosphere and the planet. In fact, if there was no naturally occurring CO_2 or other greenhouse gases in our atmosphere, the planet would be approximately 30º C cooler than it is today. This explains why we use the term "greenhouse" for these gases. They allow the incoming visible light energy in but prevent the outgoing terrestrial light energy from escaping, just as the glass in a typical greenhouse does.

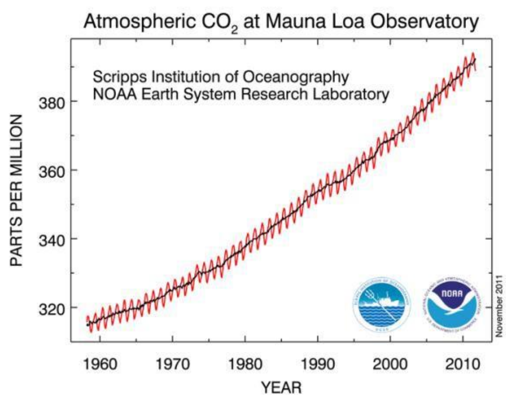

Figure 7. CO_2 concentration data from Mauna Loa Observatory from March 1958 to November 2011. Data is updated weekly and can be found on the National Oceanic and Atmospheric Administration's Earth Systems Research Laboratory site. Source: NOAA ERSL.

A problem arises, however, because the amount of CO_2 in the atmosphere is increasing. And as the amount of CO_2 increases, the amount of outgoing energy being trapped increases and, therefore, the temperature increases. Ice core data indicates that CO_2 concentration was approximately 270 parts per million (or 0.027%) in 1800 before the Industrial Revolution. Figure 7 shows CO_2 concentration data taken at the Mauna Loa Observatory in Hawaii since March 1958. What we can see is the yearly periodic oscillation due to natural growing cycles of plants that absorb CO_2 overlying the overall upward trend in the data that indicates an increase in the amount of CO_2 globally. Most scientists agree that this increase is directly related to the increase in mean surface temperature and global sea level depicted by the data in Figure 1. To understand how humans are responsible for producing CO_2 and the subsequent temperature change, we need to understand how we get energy to drive power our technology, to drive our cars, and to fuel our bodies.

Energy Consumption & CO_2 Emissions

We can think about energy as the energy stored in chemical bonds in the foods we eat or in the fuels we burn to generate heat. Both of these processes are fundamentally the same. They can be considered combustion reactions. Combustion is the reaction that takes place when organic molecules are burned in the presence of oxygen. Organic simply means that the molecule is made primarily of carbon and hydrogen. Organic materials are produced by plants in the process called photosynthesis, which takes energy from the sun and stores it in the chemical bonds of the molecules. Plants use photosynthesis to store energy. Animals take advantage of this process and eat plants for the stored energy. A series of chemical reactions called respiration details how the animals break down the organic molecules to release the stored energy. The end products of combustion reactions and respiration reactions are carbon dioxide (CO_2) and water (H_2O) and energy. Fossil fuel is decomposed plant and animal matter that has been buried and processed by heat and pressure in the earth's mantle for millions of years. It comes in the forms of coal, oil, and natural gas. All the organic material we use for energy from fire wood to food to gasoline (a by-product of oil) derives its energy from the sun through photosynthesis. The chemicals are fundamentally the same.

Using methane (CH_4) as an example, because it is the simplest hydrocarbon and commonly referred to as "natural gas", we can write the chemical reaction

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + \text{energy (890 kJ/mol).}$$

The chemical equation indicates that for every mole of CH_4 burned, one mole of CO_2 and 890 kilojoules (kJ) of energy are produced. [Note that a mole is the fundamental scientific unit for an amount of material and is simply the chemists' way to account for a lot of molecules in a tidy way, where there are 6.022×10^{23} molecules per mole.]

Another common example of a combustion reaction is that of gasoline. Using octane (C_8H_{18}) to represent gasoline, the reaction is shown below:

$$2\ C_8H_{18} + 25\ O_2 \rightarrow 16\ CO_2 + 18\ H_2O + \text{energy (5471 kJ/mol)}.$$

Here, for every 2 moles of C_8H_{18} burned, 16 moles of CO_2 and 5471 kilojoules of energy are produced. Consequently, gasoline is a much more efficient energy source than methane. However, gasoline combustion emits far more CO_2 than methane.

As an example of how we get energy through eating food, glucose ($C_6H_{12}O_6$), a sugar molecule, is broken down through a chemical process called respiration. The overall chemical reaction is

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy (2808 kJ/mol)}.$$

Here, every mole of glucose broken down through respiration yields 6 moles of CO_2 and 2808 kilojoules of energy.

The reactions above are very effective at releasing the energy stored in the reactant molecules. Our bodies, our technologies, and our societies have developed to take advantage of these chemical reactions to produce energy. In this module, we will be focusing on the carbon dioxide that is necessarily produced when we generate our energy through these chemical reactions.

Often when we talk about energy, we are actually talking about electricity. Electricity is the flow of electrical charge and is a secondary source of energy. The primary source of this energy is typically an electromechanical generator, most often driven by steam. While the steam is most often produced by burning fossil fuels, nuclear reactions are also used to generate heat to produce steam to drive turbines and generate electricity. Wind and water (hydroelectric) turbines are also used to produce electricity without steam. Photovoltaic (solar) cells try to replicate photosynthesis and turn the Sun's energy chemical energy that can be used to generate electricity. Burning oil, gas, and coal (fossil fuels) produces carbon dioxide in a similar fashion to burning methane, glucose, and octane. Nuclear, wind, hydroelectric, and solar sources produce electricity without producing carbon dioxide as a by-product.

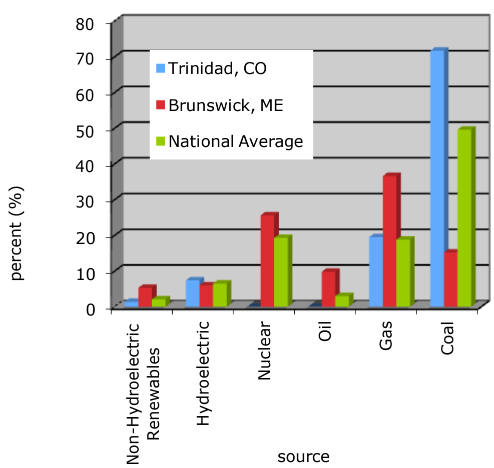

Figure 8. Source of electricity for Trinidad, Colorado, and Brunswick, Maine compared to the national average. Data compiled from http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html, a website that provides information on CO2 production by zip code.

The electricity we consume often comes from a variety of different primary energy sources depending on where we are located and the energy sources available to our local power companies. We can use Figure 8 to compare the electricity sources that involve combustion and, therefore, produce CO_2 (oil, gas, and coal) with the ones that do not (non-hydroelectric, hydroelectric, and nuclear). We can see that the fuel mix for Trinidad, Colorado, uses more combustion sources and far less non-combustion sources than the national average. The fuel mix used in Brunswick, Maine, has a higher

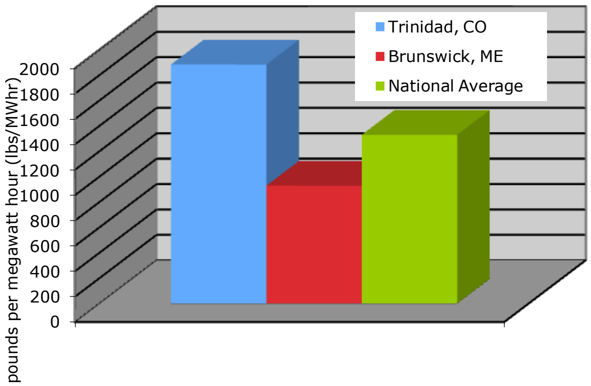

Figure 9. Amount of CO_2 produced in pounds per megaWatt hour for Trinidad, Colorado, and Brunswick, Maine, compared to the national average. Data compiled from http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html, a website that provides information on CO2 production by zip code.

percentage of non-combustions sources than the national average and Trinidad, Colorado. You can compare this to the fuel mix for the electricity you consume by entering your zip code into the website http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html. We can also find the data for the carbon dioxide emissions for each region as depicted in Figure 9. This graph shows how many pounds of CO_2 are produced for each megaWatt hour of electricity that is produced. As we would expect, since Brunswick, Maine, uses fewer combustion sources to produce electricity, less CO_2 is produced there than in Trinidad, Colorado, or nationally. This figure illustrates how humans can make choices that affect the amount of CO_2 emitted through energy production. By choosing energy sources that that do not depend on combustion of fossil fuels, humans can reduce their carbon emissions. We will use the information from Figure 9 to understand how we can make individual choices that affect our personal carbon emissions.

We can use the information in Figure 9 to calculate the amount of carbon dioxide produced for electricity consuming activities. As an example, let's consider burning a 60-Watt (W) light bulb in a desk lamp for 24 hours in Trinidad, Colorado, where 1883 pounds (lbs) of CO_2 is produced for every megawatt hour (MW·hr) of electrical energy used. To do the calculation:

$$60\ W \times 24\ hr \times \frac{1883\ lbs\ CO_2}{1\ MW \cdot hr} \times \frac{1\ MW}{1 \times 10^6\ W} = 2.7\ lbs\ CO_2$$

Because we have units of *W* and of *mW* and of *hr* in both the numerator and denominator of our fractions, our units cancel to leave us with pounds of carbon dioxide, which is precisely what we were trying to calculate. According to our calculation, 2.7 lbs of CO_2 will be emitted from burning this 60-Watt incandescent light bulb for 24 hours in Trinidad, Colorado. This number is commonly referred to as a carbon footprint.

Since we are talking about a gas, makes more sense to think about this in terms of volume. In other words, how much space would this CO_2 occupy? To estimate the volume of CO_2 in liters (L), we need to know the molecular weight of carbon dioxide (44 grams/mole (g/mol)), the volume of a mole of gas under normal conditions (22.4 liters (L)), and how to convert from English weight in pounds to metric weight in kilograms (kg). (1 kg is equivalent to 2.2 lbs). To estimate the volume of CO_2, our calculation becomes the following:

$$60\ W \times 24\ hr \times \frac{1883\ lbs\ CO_2}{1\ MW\ hr} \times \frac{1\ MW}{1 \times 10^6\ W} \times \frac{1\ kg}{2.2\ lb} \times \frac{1000\ g}{1\ kg} \times \frac{1\ mol}{44\ g} \times \frac{22.4\ L}{1\ mol} = 627\ L$$

Again, we see that units common to the numerators and denominators cancel out to give us a final answer in liters. Therefore, the amount of space occupied by the CO_2 emissions resulting from burning a 60-Watt (W) light bulb in a desk lamp for 24 hours in Trinidad, Colorado is 627 L. To assist us in visualizing how much volume this actually is, we will relate it to the volume of an everyday object, like a soda can. A soda can contains 12-fluid ounces of liquid. The question becomes how many soda cans is equivalent to 627 L. To estimate the number of soda cans, we have to know that there are 32 fluid ounces in a quart, and we need to know how to convert from the metric to the English system in volume, specifically knowing that 1.06 quarts is equivalent to 1 liter. The calculation is shown below:

$$627\ \text{L} \times \frac{1.06\ \text{quart}}{1\ \text{L}} \times \frac{32\ \text{fluid ounces}}{1\ \text{quart}} \times \frac{1\ \text{can}}{12\ \text{fluid ounces}} = 1{,}772\ \text{cans}$$

This number may impress you, but we can do one more simple calculation to further visualize this volume. Imagine we now stack and align the cans so that we make a solid rectangle with the same number of cans on each side. To figure out how many cans we would need on each side, recall that the volume of such a box is given by $V = x^3$ where x is the side length in number of cans. In our particular case, we have $x^3 = 1772$. To solve for the side length x, we calculate the cube root of 1772, which is 12.1. If we round that down to 12, then we can imagine a stack of soda cans that is 12 cans high by 12 cans deep by 12 cans wide. Given that the dimensions of a soda can are 4.8” high with a 2.5” diameter, this stack of soda cans would be approximately 4.8 feet tall and 2.5 feet deep and wide.

This demonstration illustrates how to translate an abstract idea like the amount of carbon dioxide produced during an energy consuming activity into a tangible object that you can understand better. You should be starting to understand the idea of carbon footprints, the amount of carbon emissions associated with an energy consuming activity. In homework assignment I, you will perform similar calculations to understand how your choice of light bulb affects the amount of CO_2 you are responsible for emitting.