DO-IT-YOURSELF GLOBAL WARMING SCIENCE 3rd edition
A handbook for the curious

by Jacob Bayless, Mo Chen, Charles Zhu

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Like any good science manual, the citations are listed on the back page! Don't take our word for it — check them yourself.

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1 Climate Change Science: The Greenhouse Effect

According to Wikipedia, "the greenhouse effect was discovered by Joseph Fourier in 1824 and first investigated quantitatively by Svante Arrhenius in 1896", long before the advent of modern computer models. The mechanism of the effect is quite easy to understand, but first, you must be aware of a few basic principles of physics you can find in most first-year physics textbooks (or Wikipedia):

1. All objects radiate energy, in the form of light, or "electromagnetic radiation" (UV, infrared, etc.). The hotter they are, the more energy they will radiate. This is called the "Stefan-Boltzmann Law".

The only objects that don't emit any radiation whatsoever are the ones at absolute zero, but since nothing ever reaches this temperature, we can safely assume that everything is radiating away energy. However, we often don't notice this radiation in everyday life because we are surrounded by other objects that are about the same temperature as us, plus or minus a few degrees. So even though we're emitting all this energy, we also absorb almost as much from our surroundings, so we don't all freeze to death. But you might have noticed that in the summer, cloudy nights are usually warmer than clear nights, even though cloudy days are cooler than clear days. That's because on a cloudy night, us surface dwellers absorb radiation from the warm clouds, but on a clear night, there's very little standing between us and the cold black vacuum of space (which doesn't emit very much radiation at all). So we don't benefit from all that radiation coming down from the sky, but still radiate just as much as we did before — and we quickly become quite chilly.

For an object in outer space, such as our planet, these effects are very significant. So if you don't want your planet to be cold, it's a good idea to position it next to something very hot, like the Sun. Hot objects give off a lot more radiation than cool objects.

The Stefan-Boltzmann Law is this equation [1]:

$$P = \epsilon \sigma A T^4$$

Here, P is the power, or rate of energy radiated by an object, measured in watts. The constant ϵ, which is known as the "emissivity" of an object, describes roughly how "dark" or "dull" that object is. σ is called the "Stefan-Boltzmann constant", and it's just a number thrown in to make the equation work for SI units. Its value, and values for emissivity, can be found in Section 9: Appendix A, along with other helpful numbers, in case you feel like using this formula for calculations. A is the surface area of the object, and T is its temperature, measured in Kelvins. Keeping track of the units is very important if you're doing calculations. You don't have to understand this formula to understand the greenhouse effect, though.

One last thing — most things reflect a portion of the light they would otherwise absorb. This is called the object's "albedo". The Earth's albedo is about 30% (according to NASA [2]), meaning it reflects almost a third of the light that it receives.

2. An object will heat up if it's absorbing energy faster than it radiates, and it will cool down if it's radiating energy more slowly it absorbs. Its temperature is steady when it emits energy at the same rate as it absorbs.

This is probably common sense, but it's also extremely important! If you ever need to know how warm a planet is, and you have a good idea of what its surroundings are like (that is, how much energy it gets from its star), you can get a "quick and dirty" estimate using this fact. That is, you just find what temperature it has to be in order to emit just as much energy as it's getting from its surroundings. This has very significant repercussions for the greenhouse effect.

3. The colour of light that is emitted depends on an object's temperature. The hotter it is, the more towards the "blue" end (short wavelengths) of the spectrum the light will be.

Actually, that's a bit of a simplification, since objects don't emit just a single colour, but rather a whole spread of wavelengths. But you can see the more exact meaning by looking at this graph:

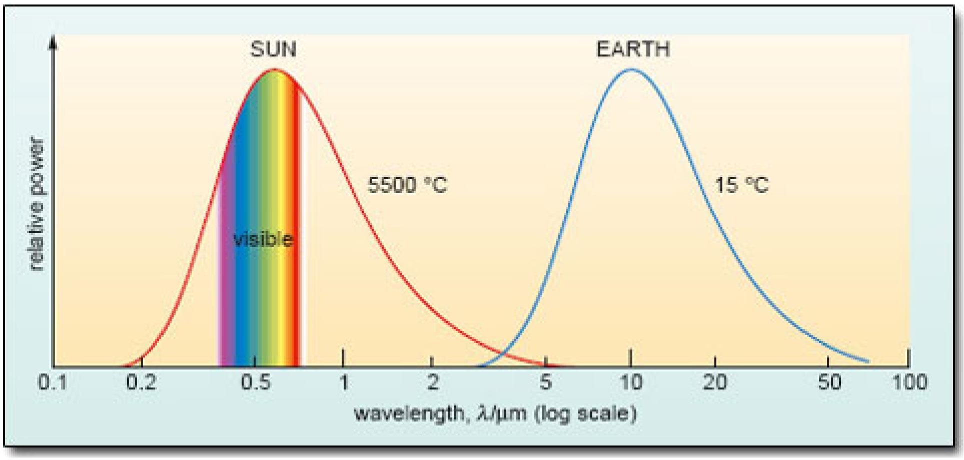

Figure 1: Radiation spectrum vs. terrestrial (Earth) radiation spectrum. Source: `http://openlearn.open.ac.uk/file.php/2805/S250_3_004i.jpg`

Here you can see that the Sun, which is very hot, emits light that is much shorter wavelengths than that emitted by the Earth. The Sun's light is mostly visible and near-infrared, whereas the Earth's is all in the very far infrared range. (An interesting side note is that the wavelengths the Sun emits the most are in the visible spectrum, even though it represents a very small fraction of the total electromagnetic spectrum. But this probably makes sense, because we wouldn't have evolved to see visible light if the Sun didn't produce any!)

This is crucial to the greenhouse effect, because it means that any substance that transmits visible light, but absorbs light in the far-infrared, will trap radiation from the

Earth, but not block incoming light from the Sun. Unfortunately, carbon dioxide (CO_2) is just such a substance, if we examine its absorption spectrum:

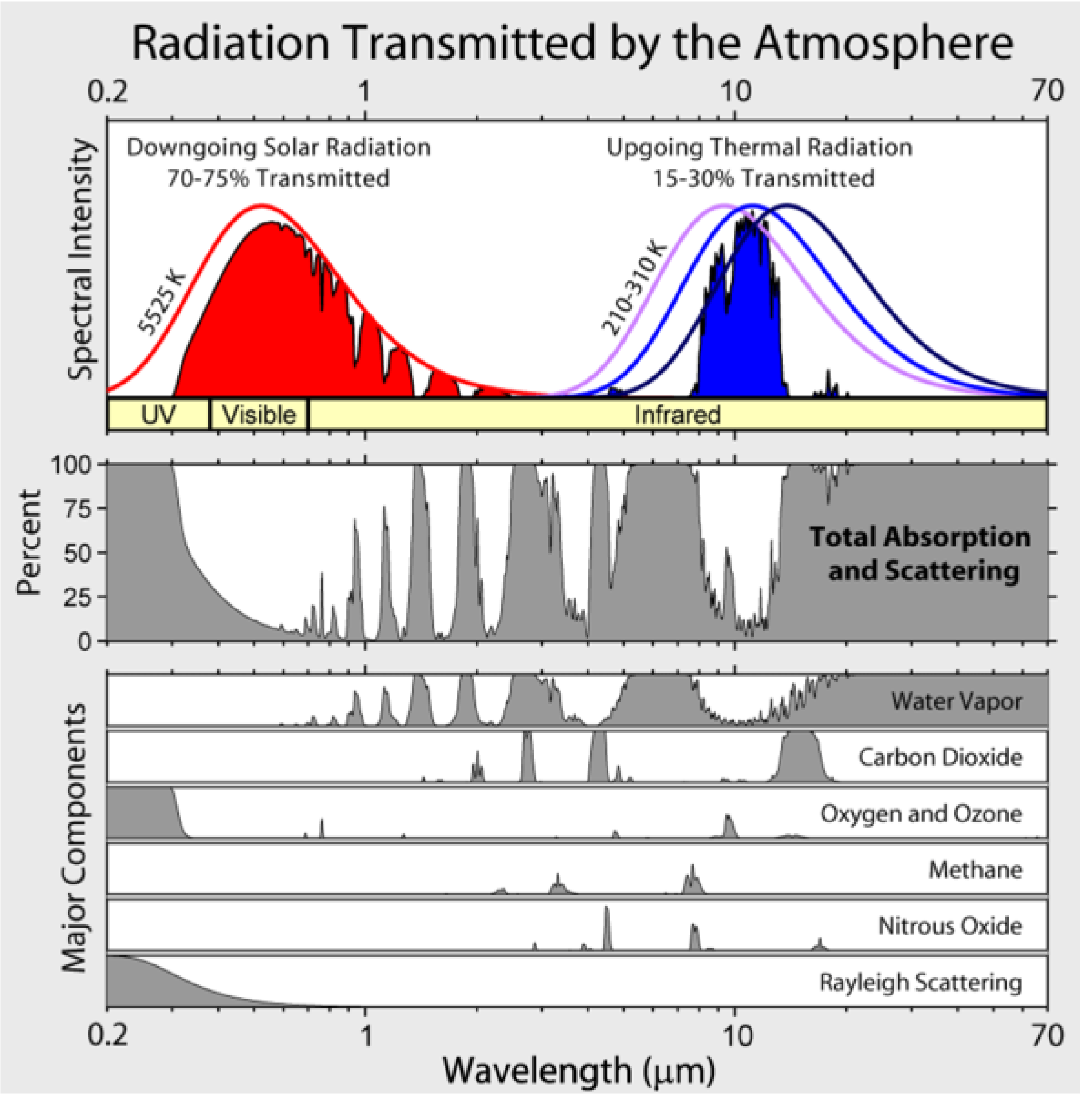

Figure 2: Carbon dioxide absorption spectrum. Source: `http://bouman.chem.georgetown.edu/S02/lect23/595px-Atmospheric_Transmission.png`

Despite the inconsistencies between the two graphs, you can see that, along with water vapour, methane, and nitrous oxide, CO_2 takes a sizeable chunk out of the infrared range right around where terrestrial radiation is the highest. All of these gasses are present in some quantity in the atmosphere, and together, contribute significantly to keeping the planet's temperature above the freezing point of water.

Armed with these principles of physics, you know about as much as Arrhenius needed to figure out why the greenhouse effect happens. You can work it out for yourself if you would like, but if you're like me, you'll find a guiding explanation helpful.

1.1 How the Greenhouse Effect Works: Step-by-Step

1. Imagine that the Earth had no atmosphere to begin with. It receives radiation from the Sun, warming it to (about) −18°C. You can get this number using the Stefan-Boltzmann law, if you'd like to try.

2. The Earth's surface emits its own radiation, because it's not at absolute zero. It emits just as much as it receives from the Sun, keeping it at a nice stable freezing temperature of −18°C...

3. But no! Suddenly, the Earth gets an atmosphere, which blocks a fraction of that earthly radiation because of greenhouse gasses. These gasses are also warm, so they emit their own atmospheric radiation. Some of it goes into space, and some of it goes back down towards the Earth.

4. Imagine you're on the Moon. The amount of radiation that you see the Earth emitting is the amount radiated from the surface, minus the amount absorbed by the atmosphere, plus the amount emitted by the atmosphere. This is less than the amount emitted by the Earth's surface alone, because some of the atmospheric radiation goes back down to the surface and is absorbed there.

5. So the fact that the Earth has an atmosphere means that it emits less energy than it was emitting without an atmosphere. It's now in a condition known as radiative imbalance: it's not emitting the same amount as it's absorbing!

6. Therefore, the surface begins to warm again, until the balance is restored. It reaches a nice comfortable average of about 15°C.

That is the basic process. There are, of course, numerous complications and complexities, but the underlying physics behind this is difficult to challenge. An interesting observation in support of the greenhouse effect is the surface temperature of the planet Venus. Venus is closer to the Sun than Earth, but much farther from the Sun than Mercury. However, Venus' surface temperature is 461°C, whereas Mercury's varies widely between day and night, but even at its hottest reaches only 430°C (and at its coldest, reaches −173°C!). Furthermore, Venus' thick atmosphere gives it an albedo of 0.75 — it reflects so much light that it actually receives less energy at its surface than does Earth! Mercury's is 0.12, reflecting only 12% of the light it receives. So despite its vastly greater distance from the Sun than Mercury, and despite reflecting vastly more sunlight than either Mercury or Earth, Venus is the warmest planet in the solar system. The greenhouse effect is responsible; Venus's atmosphere is overwhelmingly composed of carbon dioxide. [2]

2 Climate Change Science: Positive Feedbacks

Feedbacks are the main complexities in the climate system that scientists have struggled to understand in the past thirty years. However, although they are hard to identify in the climate system, the concept of a feedback is easy to understand. Fundamentally, a

Feedback	Effect
Positive	Melting permafrost — releases vast quantities of stored methane. [5]
Positive	Water vapour — as the temperature rises, so does atmospheric water vapour. H_2O is a strong greenhouse gas. [6]
Positive	Soil respiration — hotter temperatures mean microbes in the soil begin to release stored carbon dioxide. [7]
Controversial	Cloud formation — more water vapour can lead to more clouds, which both trap heat and reflect sunlight. [6]

Table 1: Some important feedbacks.

"feedback" is the way that a process can influence itself. There are two types: Positive feedbacks, where processes speed themselves up, and negative feedbacks, where processes slow themselves down.

In the climate system, a simple positive feedback is the ice-albedo effect. Ice is very white and reflective, and the ocean is very dark and absorbs a lot of light. As the ice at the poles melt, more seawater is exposed, so the ocean heats up faster and melts the ice even more — and so the process speeds itself up. That means it's a positive feedback.

There are negative feedbacks in the climate system, too. The biggest one is described by the Stefan-Boltzmann law described earlier: the hotter Earth is, the more Earth radiates to cool down; this keeps Earth's temperature relatively stable. Another negative feedback is that the more carbon dioxide there is in the air, the more effectively (most) plants will undergo photosynthesis, so the faster they'll absorb carbon dioxide. That means that, ignoring everything else, carbon dioxide should help to reduce itself back to a stable state. Unfortunately, it's not always so simple — hotter temperatures can also cause plants to produce the greenhouse gas methane when they die and decay. [3]

The real question, then, is: which feedbacks dominate — positive, or negative? Unfortunately, this is not an easy Do-It-Yourself question, unless doing-it-yourself includes doing research. Luckily, a wealth of knowledge is available on the Internet. Much of it is compiled concisely in the IPCC Working Group 1 report [4]. Another excellent source of up-to-date facts is Google Scholar (`scholar.google.com`), which lets you get information right from the scientific publications themselves.

Some other important feedbacks:

3 Climate Change Science: Finally...

By its very nature, climate change is highly related to other environmental issues (such as deforestation and air pollution), but this does not mean it is the same as them. People will frequently confuse the issue of climate change with acid rain, smog, the depletion of the ozone layer, and even radioactive waste. Sometimes this is by accident due to common misconceptions, but sometimes it can be a deliberate attempt to confuse people. Even if you will never be involved in climate science, it is important to learn the fundamentals for this reason, perhaps above all others.

4 Order of Magnitude Calculations

Ordinarily, when we do estimates, we tend to say things like "about a dozen", or "around four thousand". If we look closely, we can see that not all estimates, even verbal ones, are of the same accuracy. The vaguest sorts of estimates are essentially how many zeros are in any measurement. This is known as an order of magnitude estimate — finding the closest power of ten to the number you're looking for.

Suppose you're at a crowded hockey stadium. An order of magnitude estimate means that, instead of saying, "There are 4335 people at this hockey game", you can say, "There are a few thousand people at this hockey game". You don't have enough information to say with any precision how many people there are, or even how many thousands of people there are. But you do know enough to say with certainty that there are too many to count in the hundreds, and not enough to count in the tens of thousands.

While they may seem vague, order of magnitude calculations are actually quite a powerful tool because they allow you to compare values to see how well they measure up to each other, even without access to precise information about those values. For example, you may not know exactly how much energy is put into manufacturing a paper plate or a car, but you probably do have a reasonable guess at arriving at an order-of-magnitude estimate. Using this estimate, you can quickly conclude that making one paper plate is insignificant when compared to making a car.

Suppose you want to calculate how much fuel you use driving your car for 1 month. You could start an estimation by saying, "Well, I drive around 50 km a day" (an invaluable tool is Google Earth's ruler function; use it to trace out your path). Then you can search up your car's fuel economy on the Internet, say 11 L/100 km. Now you just multiply:

$$\frac{50\text{ km}}{1\text{ day}} \times \frac{11\text{ L gas}}{100\text{ km}} \times 30\text{ days} = 165\text{ L gas}$$

Notice, however, how many things we didn't take into account — tire pressure, passengers, road conditions, stoplights... There are a whole host of factors that could change this number. However, we do know that many of these factors are insignificant, because they may be an order of magnitude smaller (i.e., weight of passengers vs. weight of the car), so we know they can be neglected. However, some of them are significant and will reduce the trust we have in our number. The more assumptions we make, the less sure we are, so we may have to say the fuel consumption is 20,000 L, or even "on the order of 10,000 L".

Here are some rough guidelines on when and when not to use order of magnitude approximations:

USE ORDER OF MAGNITUDE WHEN

- You don't know any of your measurements for sure, to a large degree
- You "cut corners", and aren't taking into account more detailed aspects of whatever you're studying
- You want to 'play it safe' and make a conservative estimate

DON'T USE ORDER OF MAGNITUDE WHEN

- You're comparing two things that are less than around 100 times each other.
- You have access to complete information that is very precise .

5 Dimensional Analysis

Dimensional analysis is a tool used by scientists and engineers to check that their equations and calculations make sense. Dimensional analysis makes use of the units of measurement: any measure of length, for example, always has metres, feet, fathoms, or anything else that represents some distance. You can use these units to make sure that the numbers you're putting together give you the result you want.

For example, if we add two lengths together, the units of our answer better well be units of length. If we multiply two lengths together, the units of our answer should wind up being length squared (area), and so forth. If it isn't, then that's a very good indication that something is wrong!

We can also use dimensional analysis the other way — we know what units we expect for our answer, but we aren't sure what numbers we should put together to get that answer. A simple example is as follows: suppose we want to calculate the amount of CO_2 generated by driving an SUV.

There are some numbers which common sense tells us we're going to need. It should be apparent that the farther the distance you drive, the greater your emissions will be if all else is equal. Let's assume that we're driving for 50 km. Also, common sense tells us that the fuel economy of your car will play a role, too — one would expect an army tank to emit a fair bit more than a Smart Car on a given trip. We'll assume the fuel economy of the SUV is 0.1 L/km, and every litre of fuel burned creates 2.3 kg of CO_2 (2.3 kg/L). But that's all the information we have — how do we use that to get the CO_2 emissions we want?

That's where dimensional analysis comes in. Looking at the units tells us that

$$\frac{\text{CO}_2}{\text{km}} = \frac{\text{Litres of gasoline}}{\text{km}} \times \frac{\text{CO}_2 \text{ emitted}}{\text{litre of gasoline}}$$

The litres of gasoline "cancel each other out" of the equation, and thus you're left with CO_2 per km on both sides. If you want to know the total CO_2, you can "cancel out" the kilometres by multiplying by the distance traveled (50 km). So now all we have to do is plug in the numbers. *Using units as a guide, we've made our own equation!*

When you're doing dimensional analysis, you'll have to get used to working with equations using units of measurement instead of numbers. Like our last example:

$$\text{Units of CO}_2 = \frac{\text{kg}}{\text{L}}\frac{\text{L}}{\text{km}}\text{km}$$

By the way, a common way to measure CO_2 emissions is by mass: grams, kilograms, tonnes (1000 kg), megatonnes (one million tonnes), etc. Looking at this equation, can you tell what units CO_2 is being measured in?

A quick summary of the procedure:

1. Consider each unit like an algebraic constant (x, y, a, etc.). Recall from that x divided by x is equal to one ($x/x = 1$). Similarly, a unit divided by a like unit will cancel out to no units. In this case:
$$\text{Units of CO}_2 = \frac{\text{kg}}{\cancel{\text{L}}}\frac{\cancel{\text{L}}}{\cancel{\text{km}}}\cancel{\text{km}} = \text{kg}$$
2. Examine what remains, and compare it with what is expected. We ended up with kg, which is what we expected (a mass unit).
3. If you can't get the units to cancel out, then you're probably missing something from your equation. Look for a "conversion factor" to change one unit into another. Examples include density (which changes volume into mass), or speed (which changes distance into time).

Some helpful rules:

- The "x" in a^x (some number to the x^{th} power) has no units. After all, what does it mean to be "to the power of a metre?"
- Ratios (such as x/y) will have no units if both the numerator (x) and the denominator (y) use the same units. That's because the units cancel out.
- Counting numbers (such as the number of apples) do not have units.

Beware that dimensional analysis can't be used to find absolutely everything — you need sensible data to plug in once you've found a formula, in order for it to make sense. That is, just because I have might find a value measured in metres per second does not mean I've found the speed of sound. It could be the mean in-flight velocity of a European swallow. A value like 0.3 kg/s could be how fast a factory makes copper wire, or how fast Joe the hot dog eating champion devours wieners. If you put nonsense data into a sensible equation, you will get nonsense results back out.

6 Try It Out!

The reason that we are discussing dimensional analysis and order of magnitude calculations is because the two can be combined to be very useful for understanding your carbon emissions. Have you ever wondered just how worthwhile it is to ride a bicycle to work instead of driving, or to replace incandescent light bulbs with compact fluorescents? By doing a quick order of magnitude calculation, and using dimensional analysis to help you with it, you can get a good idea of which actions reduce your carbon footprint significantly, and which ones don't. It is, in fact, a very empowering tool because it gives you the ability to obtain *your own* figures and estimates when others are not available, or when you don't trust advertised claims.

To look at the above example, let's do a quick calculation for ourselves. Remember that the more effort you put into this calculation, the more precise your numbers will be. But since this is just an order of magnitude calculation, what we're looking for is to see whether one action is significantly more effective than the other (ie, a *hundred or more times* more effective) or whether they're about the same.

6.1 Comparing a car and a bicycle:

In the previous section, we found a way of calculating the carbon emissions of driving a car, so this example should be pretty easy — we just need to include the fact that the trip to work is driven many times per year.

$$\frac{\mathrm{CO_2}}{\mathrm{Year}} = \frac{\mathrm{kg}}{\mathrm{L}} \times \frac{\mathrm{L}}{\mathrm{km}} \times \frac{\mathrm{km}}{\mathrm{trip}} \times \frac{\mathrm{trips}}{\mathrm{year}}$$

I'm going to assume here that the car is a Honda Civic (because they're so common!), and for simplicity I'll trust their published fuel economy figures of 29 MPG [8]. Typing "29 miles per gallon" into Google gives 12.3291675 kilometers per liter (for even quicker conversions, download the unit and energy converters from `http://wps.prenhall.com/esm_aubrecht_energy_3/`). But since this is only an order of magnitude calculation (meaning chances are the other digits aren't accurate), we'll do just fine using 12 km/L, which is the same as 0.08 L/km. When you do the calculation, feel free to use your own car's figures. Better yet, figure out your car's actual efficiency by reading the odometer each time you refill your gas tank.

Google Earth allows you to conveniently estimate the distance between your home and your workplace (as stated before, you can use the "ruler" tool to trace out your driving route!). In this example we'll assume that it's a 6 km round trip, an easy biking distance. The third piece of information we need is how many kg of CO_2 are emitted by burning a litre of gasoline. In the previous section, we just assumed we knew this number to be 2.3 kg of CO_2. Indeed, it's very hard to get a precise value for this without prior knowledge because modern gasoline is a mixture of many different petrochemicals. Nonetheless, a "quick-and-dirty" estimate for this number is provided in the Section 9: Appendix A.

Using our formula, we get $2.3 \times 0.08 \times 6 = 1.1$ kg of CO_2 per round trip.

Over the course of the year, there are about 260 workdays, so if you drove to work each day you'd emit about 290 kg of CO_2. In comparison, the bicycle is emissions-free (if you're wondering why we don't need to consider an increased breathing rate due to pedaling, see the Section 8: Frequently Asked Questions). **Thus, the total emissions savings amount to 290 kg.**

6.2 Replacing light bulbs:

A lot of publicity has been given to compact fluorescent light bulbs (CFLs). Australia and Ireland have already announced plans to ban incandescent bulbs [9].

Canada will be banning them by 2012 [9]. CFLs are rapidly becoming the iconic solution to global warming, so it's worth taking a look at the effect they have (especially since CFLs contain trace amounts of mercury [10] and can pose an environmental hazard if not handled correctly).

Once again, we can use dimensional analysis to come up with an equation to help us here. We know we're looking for CO_2 emissions, but how do we get there? Well, once again there's a few things we know are important.

- How many incandescent light bulbs are in your house?
- How much power does each use?
- How much power do compact fluorescents use?
- How long do you leave them on each day?
- How do we turn energy use into CO_2?

Another important thing is to understand that power is a rate of energy usage. That means that

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}, \text{and therefore Energy} = \text{Power} \times \text{Time}$$

Power is often measured in watts (or kilowatts). Household energy use is often measured in kilowatt-hours (kWh). One kilowatt-hour is one kilowatt of power applied over the period of one hour.

Dimensional analysis points to an equation like this one:

$$\text{kWh} = \text{Lightbulbs} \times \frac{\text{kW}}{\text{Lightbulb}} \times \text{hours}$$

Every house has a different number of light bulbs, so counting how many are in your house gives the most accurate estimate. For an average house I'll guess that there's about

25. An incandescent bulb is generally about 60 Watts (0.06 kW), and an equivalent CFL is about 13 Watts (0.013 kW). Each light is probably on for 8 hours a day; more or less depending on how conscious you are about turning off your lights. Remember again that it's not important to be extremely precise.

Energy to power your light bulbs is generated by power plants and distributed over long-distance power lines. There are lots of different kinds of power plants, but the main sources are coal, natural gas, hydro, and nuclear. The first two emit lots of CO_2, and the latter two emit very little. How do you decide which kind to include in your calculations? Well, I like to assume (optimistically, perhaps, but BC Hydro has promised us a mandate) that if we're reducing energy consumption in order to reduce our greenhouse gas emissions, the first power plants that would be shut down will be coal power plants because they emit the most greenhouse gases per unit of energy [11]. Therefore, we can assume that all energy we save will come from coal-powered sources. There are other ways to examine this, however. For example, you could take a weighted average of all of the different sources of power in your province. Or if a new power station is being proposed in your area, you could assume that turning on additional light bulbs is behind the need for that station, so you could use its predicted emissions in your calculation. Either way, since we're assessing the viability of CFLs as a solution, it makes sense to first assume that power comes from coal because this is a "best case scenario" — any reduction in power usage adds up to a very significant CO_2 savings. The efficiency of a Canadian coal plant is about 37% [11], which means that 37% of the energy in coal becomes electricity. This figure is from 1988, and efficiency has no doubt risen since then, but higher efficiencies will only reduce the CO_2 savings.

So to turn kWh into kg of CO_2:

$$\mathrm{CO_2} = \mathrm{kWh} \times \frac{\mathrm{Coal}}{\mathrm{kWh}} \times \frac{\mathrm{CO_2}}{\mathrm{Coal}} \div \mathrm{Efficiency}$$

If you're wondering why we divide by efficiency instead of multiplying, it's because it stands to reason that a low efficiency should increase CO_2. Dividing by a number less than one does exactly that, which is a good sign that it's the correct operation. (If this is too hand-wavy of a calculation, remember that Efficiency = Energy Out/Energy In, and CO_2 is created when making Energy In, and do some algebra to get the same conclusion). So let's do the calculation:

Incandescent:

$$25 \text{ lightbulbs } \times 0.06 \text{ kW } \times 8 \text{ h } = 12 \text{ kWh}$$

$$12 \text{ kWh } \times \frac{1 \text{ kg coal}}{7.2 \text{ kWh}} \times \frac{3.5 \text{ kg CO}_2}{\text{kg coal}} \times \frac{1}{0.37} = 15 \text{ kg CO}_2$$

CFL:

$$25 \text{ lightbulbs } \times 0.013 \text{ kW } \times 8 \text{ h } = 2.6 \text{ kWh}$$

$$2.6 \text{ kWh } \times \frac{1 \text{ kg coal}}{7.2 \text{ kWh}} \times \frac{3.5 \text{ kg CO}_2}{\text{kg coal}} \times \frac{1}{0.37} = 3.4 \text{ kg CO}_2$$

Net:

$$15 \text{ kg } - 3.4 \text{ kg } = 11.6 \text{ kg CO}_2 \text{ (reduced)}$$

which is 11.6/216 = 5% of the emissions from driving a car, as we calculated in the previous question. Also, the average person doesn't drive 6 km a day, some drive 30 to 50 km a day; if the average is around 30, then we have around 1000 kg of CO_2 emitted per year. So, armed with a pencil and the back of an envelope, you can see that the CFLs aren't as much of a "wonder invention" as some people make it out to be, and biking instead of driving seems to pay off.

Homework? Sure! Try these: assuming an airplane has the same fuel consumption per kilometre per passenger as a single-occupant Toyota Prius (a good estimate for long-haul flights), calculate how much CO_2 a passenger is responsible for on a flight from Vancouver to Hong Kong. Or try figuring out the emissions involved in shipping food from California to BC by truck (very roughly). Or, try estimating how much energy your microwave uses to run the clock compared to heating up food (assuming the clock never turns off). Figure out what you want to assume, and remember that if it only makes a 5% difference, just neglect it. Have fun!

7 Debating Tips

Evidence supporting one side does not refute evidence for the other side: Suppose someone finds that Pluto is warming up, which, in their mind, lends credibility to the idea of solar warming. Suppose that other studies confirm this. This person then contends that the IPCC report stating that solar heating is negligible compared to anthropogenic (human-caused) heating is incorrect. This is bad logic: this person is using the fact that his/her data is correct to boost the validity of his/her conclusion versus the IPCC conclusion. Simply because a study's data is correct does not mean its conclusion must be as well. For example, there is no reason why Pluto and Earth have to be warming for the same reason (see the frequently asked questions for more detail on this particular objection).

Correlation does NOT necessarily entail causation: And speaking of which, let's talk a bit about correlation, which is a fancy term meaning a relationship between two quantities (such as mass, volume, energy, number of puppies, etc). Correlation can be positive (increase in one quantity means an increase in another), negative (increase in one means a decrease in another), or nonexistent. Correlation may indicate causation, or it may not. A graph showing a positive correlation between driving speed and crashes may be interpreted, rightly, as meaning driving at high speeds results in more crashes. It can also suggest, nonsensically, that crashes cause high-speed driving. You have no way of knowing just from the graph, and you need more information to figure out causation. A third possibility is that both quantities are affected by a third, un-graphed quantity. Suppose you do a graph, which shows a "correlation" between long marriage and receding hairline. It's nonsense to suggest that receding hairlines cause long marriages, or (I suppose) long marriages cause receding hairlines. But both could be due to age. A fourth possibility is that the correlation is by accident. Someone once did a wonderful correlation on solar power and stock market prices…

The validity of a study can be challenged: A source's reputation can be doubted. Check the funding of studies. Find out what organizations certain scientists are involved in. Remember, however, that just because a scientist is affiliated with the American Association of Petroleum Geologists or the Sierra Club does not mean he or she cannot do a good study. Once you become suspicious, challenge a paper's methods of data collection and analysis, or, if the methods are very complex, look for other papers that do so (they often do exist).

You don't have to trust other peoples' interpretations: If your "opponent" has given you a set of studies, read them yourself when you get the time. If you find fault with your opponent's analysis, mention it to him or her, and be prepared to state what fault you found. We encourage you read our document with a grain of salt; if you find something strange, go look at our sources!

Nobody's right all the time: If you can't challenge an argument you're presented with, you might consider re-evaluating your own position. You might not expect it, but what it often takes to convince a contrarian is to concede when they've made a good point.

8 Frequently Asked Questions

Q: Isn't the Sun a much more important factor in climate than greenhouse gasses?

A: Of course it is, since that's where all our energy comes from. But to determine if the Sun is actually causing the present climate change, it would be prudent to see if the Sun is changing. Fortunately, we've been measuring solar output for a very long time:

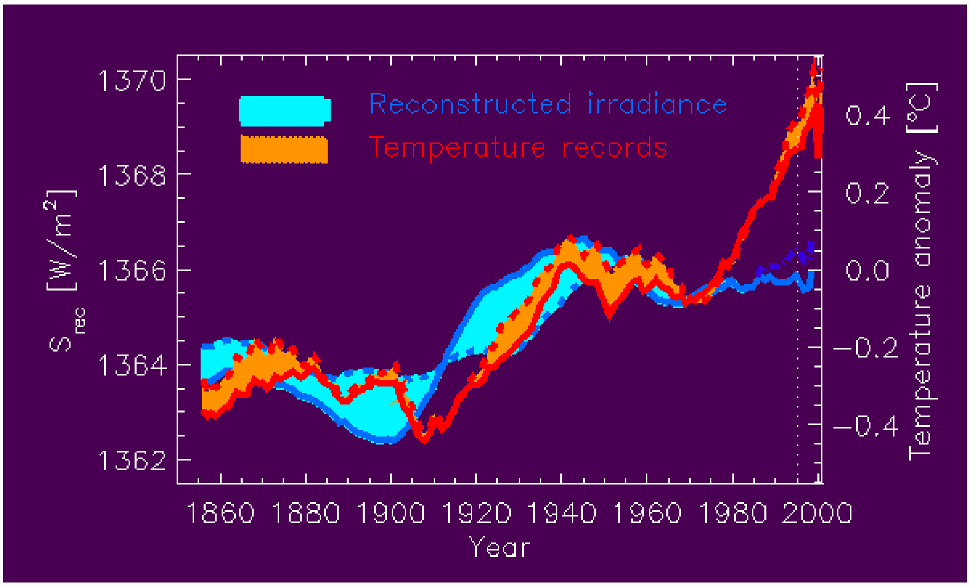

Figure 3: Solar irradiance record (presented in flamboyant, unnecessary colours). Source: Max Planck Institute for Solar System Research — `http://www.mps.mpg.de/images/projekte/sun-climate/climate.gif`

This provides a good "hand-wavy" picture that shows that solar irradiance was likely responsible for a large part of the temperature rise in the early 20th century, but less so in the present. To show definitively that it is not responsible, however, Section 10: Appendix B provides two papers on the subject by Meehl et al., which show why scientists are very sure that there is an anthropogenic (human-caused) influence in the climate system [12].

Q: Isn't water vapour a much more important greenhouse gas than carbon dioxide?

A: It is, and it isn't. Water vapour is important in the sense that there is much, much more of it in the atmosphere, so it is responsible for the vast majority of the greenhouse effect [6]. It is also a key part of many feedbacks (above in table 1). However, it isn't important because extra water vapour added to the atmosphere won't stay there. The next time it rains, all that extra water winds up in puddles at your feet! Carbon dioxide, on the other hand, CO_2 remains in the atmosphere for hundreds of years [13] so its emissions are very important.

The effects on climate of water vapour as a greenhouse gas is not well-understood; there is no reliable atmospheric water vapour concentration data. It is unclear which of the many feedback loops of water vapour is the most significant. Most importantly, changes in water vapour concentration is considered to be the result of other feedback systems. For example, if other greenhouse gases cause the Earth to warm up, there would be more evaporation, leading to more water vapour [14]. In contrast, we can directly control the emissions of other greenhouse gases like CO_2 (and thus evaporation and water vapour).

Q: Aren't humans are responsible for only a small fraction of CO_2 emissions?

A: Yes; according to the IPCC, humans are responsible for only 3% of greenhouse gas emissions (see Figure 4). Most CO_2 emissions come from natural sources — decomposing trees, animal respiration, and numerous other places. But remember that these sources have been around for thousands of years, and yet carbon dioxide concentrations have been quite stable over that time [15]. There is, in fact, something very different about the CO_2 that humans are responsible for: it came from underground!

Carbon dioxide goes through a cycle, similar to the hydro cycle that you probably learned in elementary school (rain, river, ocean, evaporation).

- All of the carbon that you emit when you exhale comes from sugars that your body has metabolized to produce energy.
- Those sugars were produced by plants, or by animals that ate plants (or animals that ate animals that ate plants).
- All of the carbon atoms in those sugar molecules were obtained by plants from the atmosphere, via photosynthesis.

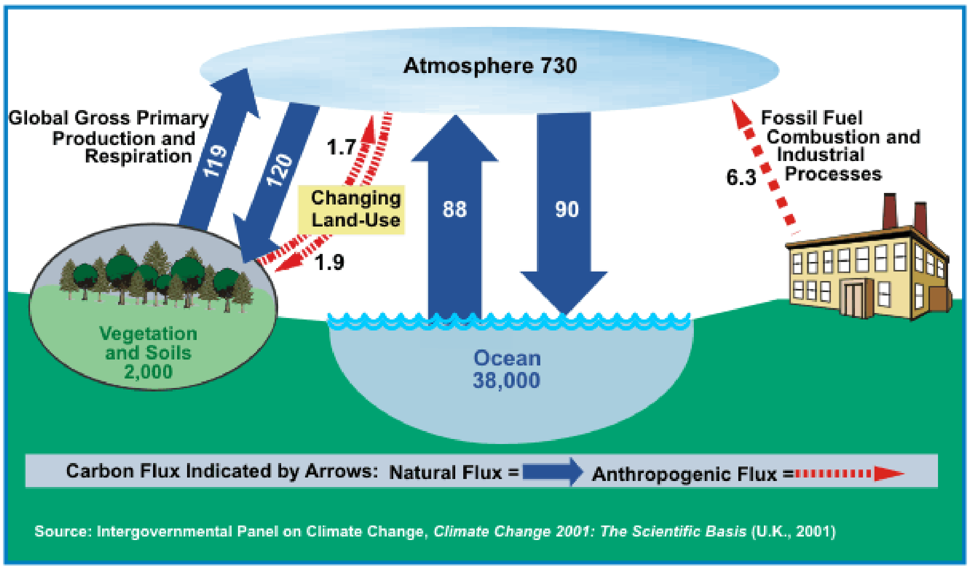

Figure 4: Anthropogenic CO_2 emission processes. Source: `http://www.exotichide.com/G/ipcc.gif`

So despite the vast quantity of carbon dioxide emitted by respiration, it must necessarily be balanced by photosynthetic uptake of carbon. The important parts of the carbon cycle to examine, then, are sources wherein carbon is added to the atmosphere which has not been in it for millions of years. There are two major sources of this carbon:

- Volcanoes
- Fossil fuels

As it happens, volcanic CO_2 emissions, while significant, are dwarfed by human emissions [16]. This is why we are witnessing the trend shown below:

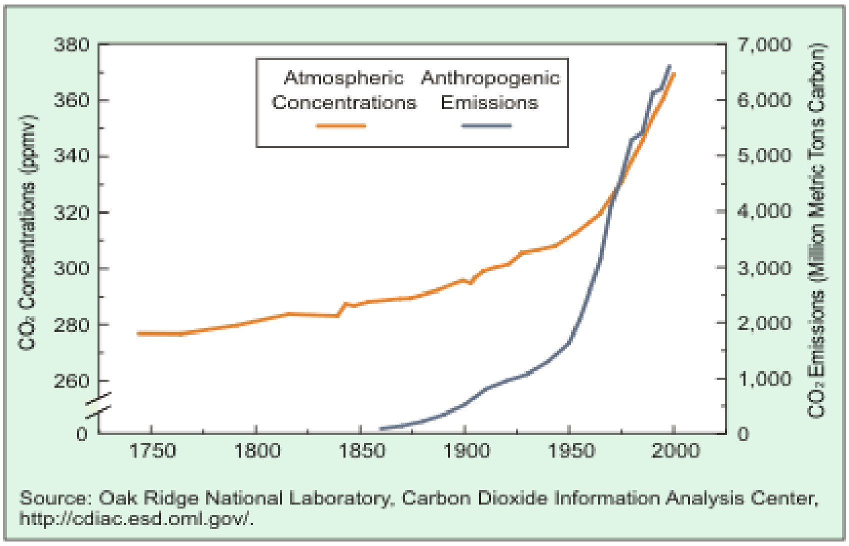

Figure 5: Comparison of atmospheric CO_2 with anthropogenic emissions. Source: `http://www.exotichide.com/G/ipcc.gif`

Scientists have other ways of knowing that the increase in carbon dioxide is coming from us as well. For a more detailed explanation, see [4],[12],[13].

Q: Did global warming stop in 1998?

A: Unfortunately not. However, this is a very frequently asked question, and it's based on the fact that 1998 is the warmest year on record (tied with 2005). This is a very poor way to analyze data, often known as "cherry-picking". As explained by NASA's Goddard Institute for Space Studies in their 2005 summary,

> "The highest global surface temperature in more than a century of instrumental data was recorded in the 2005 calendar year in the GISS annual analysis. However, the error bar on the data implies that 2005 is practically in a dead heat with 1998, the warmest previous year. [...]
>
> Record warmth in 2005 is notable, because global temperature has not received any boost from a tropical El Niño this year. The prior record year, 1998, on the contrary, was lifted 0.2°C above the trend line by the strongest El Niño of the past century.
>
> Global warming is now 0.6°C in the past three decades and 0.8°C in the past century. It is no longer correct to say that 'most global warming occurred before 1940'."
>
> Source: `http://data.giss.nasa.gov/gistemp/2005/`

However, as one might expect, the global average trend for temperature has been continuously upward.

Q: Was 1934 the warmest year on record?

A: 1934 has been getting a lot of publicity recently, because it was the warmest year on record... in the United States. This figure should clear things up:

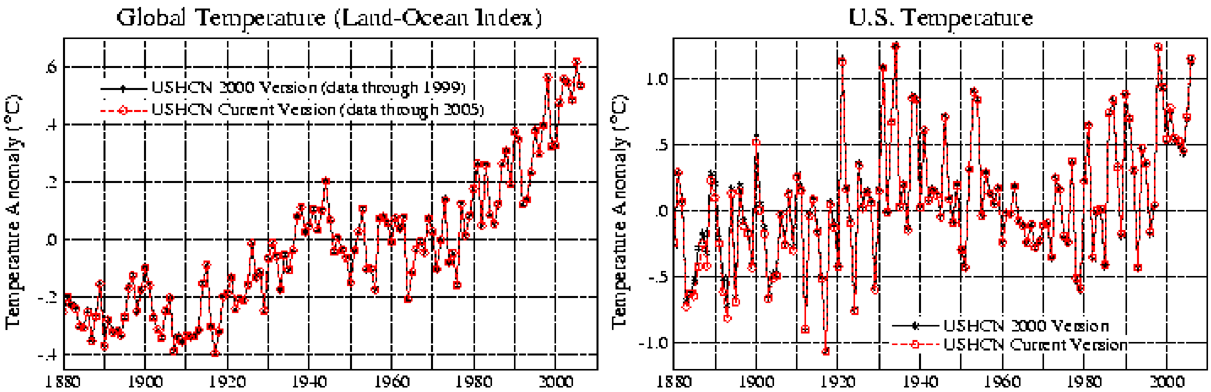

Figure 6: Comparison between U.S. and global temperatures 1880-2000. Source: `http://data.giss.nasa.gov/gistemp/graphs/USHCN.2005vs1999.lrg.gif`

As might be expected, the temperature record in any one country looks very different than that of the globe, and shows considerably more variation. However, a record-breaking heat wave in the US in one year might be met with a record-breaking cold snap in Russia in the same year, and vice-versa. That's why global temperatures are the important data to look at, rather than headlines touting extreme local temperatures.

Q: Aren't the other planets warming as well? Isn't that suspicious?

A: Indeed they are [17]. Pluto, Mars, Neptune's moons, and some other planets all seem to be undergoing some kind of warming. Suspicious indeed! It might lead you to the conclusion that, since "there are no SUVs on Mars", global warming is natural and caused by the Sun (first question). I would like to point out that there are eight (or nine) planets [2], and at any time one might expect half of them to be warming and the other half to be cooling, so hearing that this is the case is hardly exceptional.

For example, when it comes to warming on Pluto, it is important to note that its year is 248 Earth years long, and the planet itself was only discovered in the early twentieth century (and for a very long time, it was barely a speck of light in a telescope). In some ways, it still is — this is the highest resolution image we have of Pluto as of this writing.

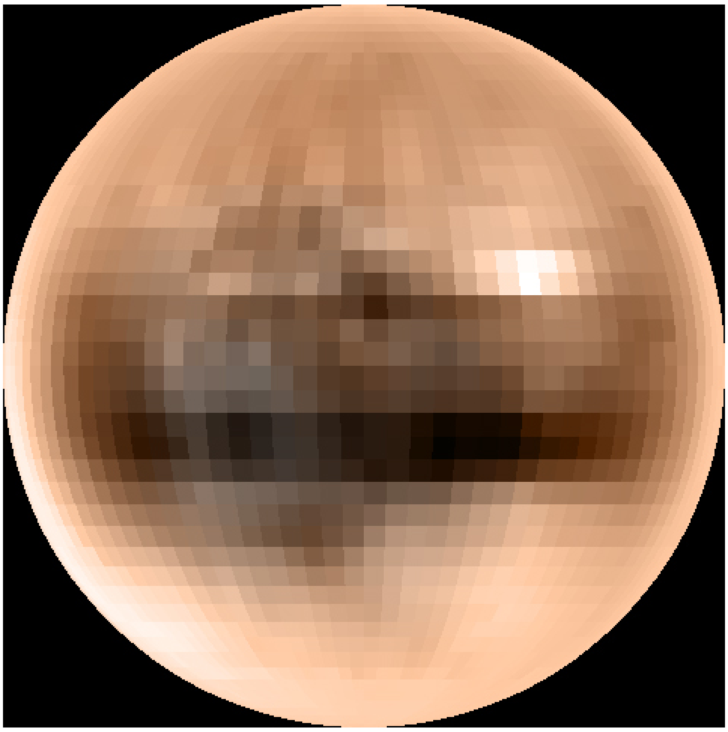

Figure 7: Pluto, highest resolution yet as photographed by NASA scientists. Source: `http://antwrp.gsfc.nasa.gov/apod/ap010319.html`

Having not observed the planet for even one of its own years (let alone observing it closely), I find it hard to conclude that the planet's warming is due to something as simple as the Sun warming up. However, you may draw your own conclusions. Of course, there are other claims around the Internet of planets (Mars, Mercury, etc.) heating up. Even if we suppose all these statements are backed by studies of some kind, we still must contend with the fact that if the Sun were heating things up, we'd notice it by observing the Sun as well as the Earth. As we've currently found that solar irradiance is around 13.3 times less influential than human-made warming [12], anyone wishing to propose a solar-based warming theory would also have to explain such data as well as tout their planetary heating evidence. The papers in the appendix regarding these warming planets all cite non-solar causes.

Q: If scientists can't predict the weather tomorrow with certainty, what makes them so sure about the climate in 2050?

A: The weather is unpredictable, but the climate is not. It is difficult to predict what the weather will be tomorrow in Vancouver, but it is easy to say with certainty that over the course of the year, Vancouver's weather will be colder than that of Mexico City. Climate's predictability boils down to averaging: Global warming usually refers to the change that occurs in global temperatures averaged over ten or fifteen years. This smooths out the random variation from such things as day-to-day weather, seasonal varations, and El Niño and La Niña, ensuring that you're looking at long term trends.

This is common across many fields of science. Physicians might tell you roughly how many people in the 18 to 24 age category will eventually get cancer, but they will be hard pressed to say if Alice from Calgary will. Economists can estimate how much Canadians will spend on produce next year, but not how much Bob from Winnipeg will spend tomorrow. No climate scientist purports to know whether it will rain in Moscow on June 14, 2051!

9 Appendix A: Useful Constants

* Note: $\text{unit}^{-x} = 1/\text{unit}^x$
** All constants from Wikipedia and/or Google Calculator, unless stated.

Constants

Stefan-Boltzmann Constant:	$\sigma = 5.67 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4}

Data (see "Solar System Facts" for more):

Emissivity of Earth:	$\sigma_E \approx 0.612$
Radius of Earth:	$R_E = 6.378 \times 10^6$ m
Avg. Temp. of Earth (without atmosphere):	$T_E \approx 255$K (-18°C)
Albedo of Earth:	$A_E \approx 0.3$
Emissivity of Sun:	$\sigma_S \approx 0.612$
Radius of Sun:	$R_S \approx 6.955 \times 10^8$ m
Temperature of the Sun Surface:	$T_E = 5778$ K (5504°C)
Distance from Earth to Sun:	$L = 1.496 \times 10^11$ m
Solar Constant (Flux of Sun's energy at Earth):	$I = 1366$ W m^{-2}
Specific Heat of Water:	$c_{\text{water}} = 4.2 \times 10^3$ J kg^{-1} K^{-1}
Density of water (at 20°C):	$\rho_{\text{water}} = 998.2$ kg m^{-3}

Conversion (see Aubrecht's Energy website for more):
Temperature in Kelvin (K) = 273.15+temperature in degrees Celsius
1 kilowatt-hour (kWh) = $3,600,000$ Joules (J)

Useful Chemical Conversion (our own estimate):
1 L of gasoline gives 2.30 kg of CO_2
1 kg of coal gives 7.2 kWh
1 kg of coal gives 3.5 kg of CO_2

10 Appendix B: Further Reading

An article from Scientific American, illustrating the past importance of CO_2 in mass extinction events:
`http://www.chicagocleanpower.org/ward.pdf`

This is a good source of land-ocean temperature records:
`http://data.giss.nasa.gov/gistemp/graphs/`

Oak Ridge National Laboratories (ORNL) is a good source of all sorts of fascinating studies. This is a link to their environmental sciences division:

http://www.esd.ornl.gov/

Figures from the US Department of Energy often come from ORNL:
http://www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html

George Monbiot (author of the book Heat: How to Stop the Planet from Burning) has many excerpts from his book, as well as tons of other articles, available on his website:
http://www.monbiot.com/

Summary of various contributions to climate change:
http://www.greenfacts.org/en/climate-change-ar4/images/figure-spm-2-p4.jpg

The intergovernmental panel on climate change (IPCC), created by the United Nations, released a series of reports (totalling more than a thousand pages), most recently in 2007, detailing climate change's physical basis, human cause, and solutions. Essentially every topic related to climate change is covered by the reports, making them an excellent source for information.
http://www.ipcc.ch/ipccreports/assessments-reports.htm

We recommend Gordon J. Aubrecht's textbook, Energy: Physical, Environmental and Social Impact. It's on the technical side (a good handle of first-year physics may be needed), but has some amazing statistics, charts and data for you to pore over. Free and highly useful spreadsheets, and more data, are posted on the book's companion website,
http://wps.prenhall.com/esm_aubrecht_energy_3/

Fuel economy of various vehicles, ranked by the (US) EPA and Department of Energy:
http://www.fueleconomy.gov/

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