



# Some Simple Physics of Global Warming

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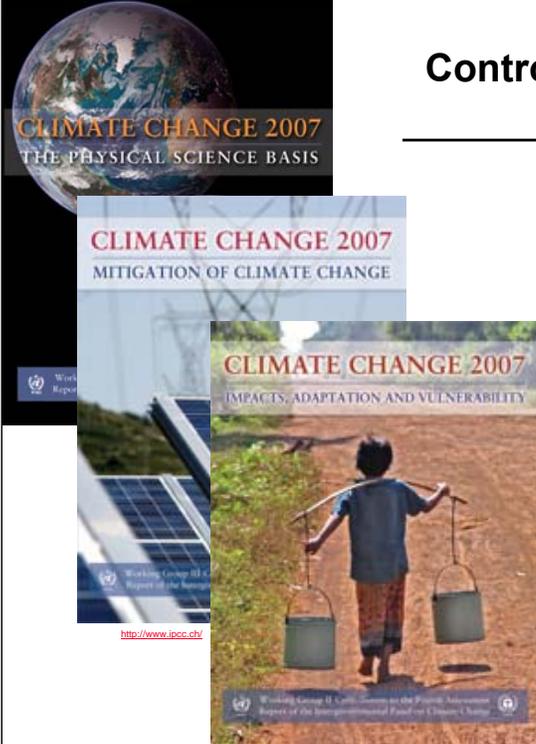
JY Tsao

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2008 April



- I'm Jeff Tsao. I'm an applied physicist at Sandia Labs, where my work most recently has centered on energy efficiency technologies, like the use of semiconductors to make better lights. During the course of that work, I've off and on had the opportunity to delve into global warming issues, and I'm happy to be able to share a little bit of that with you today.
- Now, first off, how many of you know about global warming? How many of you have seen Al Gore's movie "An Inconvenient Truth"? How many of you think global warming is real? How many of you think global warming is not real? How many of you think global warming might be real, but you're not sure what should be done about it?



## Controversy, complexity, and uncertainty

**Description of confidence**  
On the basis of a comprehensive reading of the literature and their expert judgement, authors have assigned a confidence level to the major statements in the Report on the basis of their assessment of current knowledge, as follows:

Terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

**Description of likelihood**  
Likelihood refers to a probabilistic assessment of some well-defined outcome having occurred or occurring in the future, and may be based on quantitative analysis or an elicitation of expert views. In the Report, when authors evaluate the likelihood of certain outcomes, the associated meanings are:

Terminology	Likelihood of the occurrence/ outcome
Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

<http://www.ipcc.ch/>

- Well, I don't blame you. This is a subject with a lot of controversy, a lot of complexity, and a lot of uncertainty.
- To emphasize that point, here I show the current definitive references on global warming. These are three volumes published at the end of last year by the United Nations Intergovernmental Panel on Climate Change (sometimes just called the IPCC). In fact, it was for the work documented in these volumes that the IPCC shared last year's Nobel Peace Prize with Al Gore.
- All three of these volumes are massive -- roughly 1000-pages long each. This is a double-sided print-out of just the first volume.
- These volumes are massive, I think in part because global warming is an extremely controversial subject, so the IPCC couldn't just wave their hands, but had to put in a lot of the gory technical details.
- They're also massive in part because global warming is a genuinely complex subject that blends physics, chemistry, biology, economics, along with issues of ethics and morality. What are the ethics, e.g., of leaving for our children and grandchildren a legacy of global warming? Or what are the ethics of the wealthy nations vis-a-vis the poorer nations, if it is the wealthy nations that have been the dominant cause for global warming, but the poorer nations that may suffer the most?
- Finally, they're massive in part because there is a lot of uncertainty. If there were certainty, you could just state your results in a few sentences. There's so much uncertainty, in fact, that the IPCC actually devised a nomenclature so that whenever they say something you'd know exactly how certain they are of what they are saying. For example, if they say something with very high confidence, it means they believe it has at least a 9 out of 10 chance of being correct. If they say something with medium confidence, it means they believe it has about a 5 out of 10 chance of being correct. As far as I know, this level of carefulness is unprecedented in the history of panel reports, and is just one more indication of the controversy, complexity and uncertainty associated with global warming.



## Topics

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- **The Earth's Delicate Heat Balance**
- **Earth's Temperature History**
- **The Earth's Sluggish Carbon Balance**
- **Humanity's Appetite for Energy and Carbon**

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- **What Can We Do?**

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- In this presentation, though, I'm going to try to stay away from controversies and uncertainties. Instead, I'm going to focus on some of the simple but interesting physics that underlies global warming. We'll even do some calculations together, so that you can get an idea of how little pieces of math (that you wondered why you were learning over the years) can end up being useful. I don't want to go overboard, and I'm slightly afraid that I have. But I also want to share with you a sense for how important simple quantitative calculations can be in trying to understand things. So I'll try to go slow for some parts, and if I'm still going to fast, just interrupt me and ask questions! For that matter, even if I'm not going too fast, feel free to interrupt me and ask questions. I'm hoping to keep this presentation as informal and conversational as possible.
- Here are the topics that I'm planning to cover.
- I'll start by talking about the earth's delicate heat balance. How many of you have read a book called the "Rare Earth," by Peter Ward and Donald Brownlee? Well, it basically talks about how unlikely it is that the earth, or any world, for that matter, would have the peculiar characteristics that it has. In fact, one of the most unlikely of those characteristics is its average temperature. Does anyone know what that temperature is? It's 14C (57F), just about perfect for carbon and water based life like us.
- Then I'll talk about the earth's temperature history – the end result of the earth's delicate heat balance as it has varied over geological time scales.
- Then I'll talk about the earth's sluggish carbon balance. Carbon dioxide, as you all know, is the molecule that is causing global warming, and so understanding its role and its dynamics on the earth is crucial to understanding what we might be able to do about it.
- Then I'll talk about humanity's appetite for energy and carbon. As you also know, we wouldn't be having a carbon problem if we didn't have an enormous appetite for energy. So understanding that appetite for energy again is crucial to understanding what we might be able to do about our carbon problem.
- Finally, I'm afraid I ran out of steam as I was preparing for this presentation, so I will only have a little bit to say about this last topic (what can we do about global warming). I apologize in advance. Maybe next time!



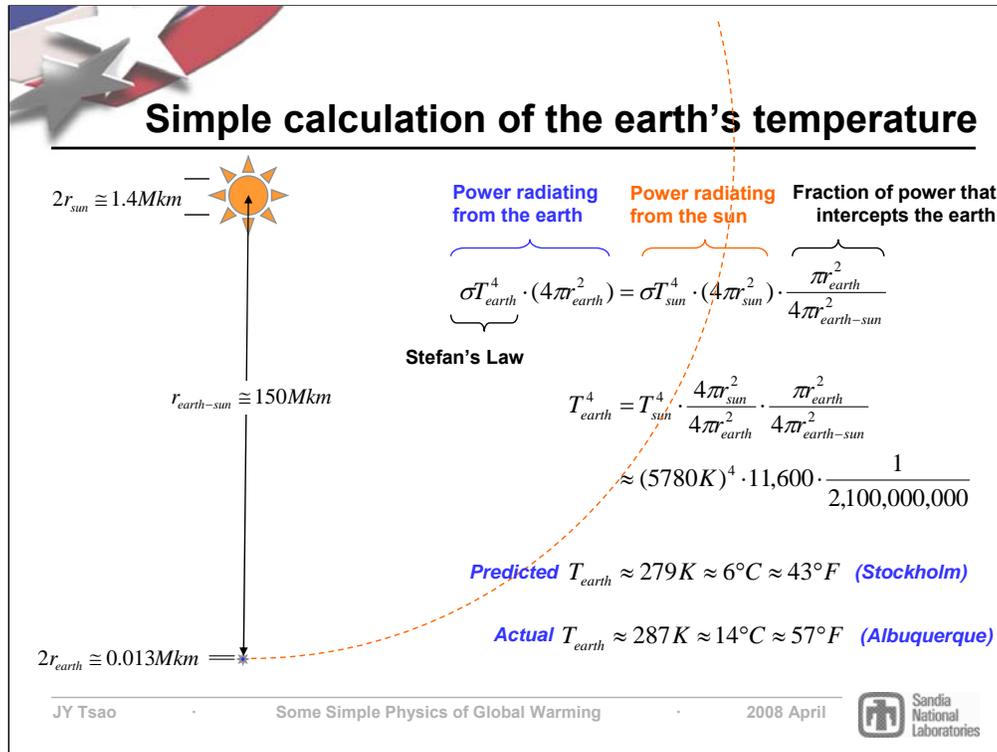
# Earth's Delicate Heat Balance

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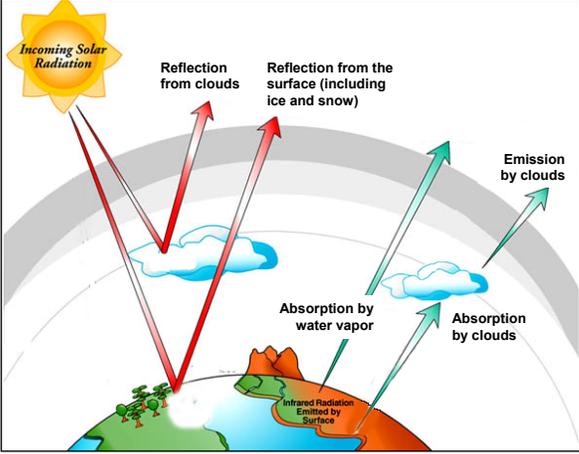


- Let's start with the earth's delicate heat balance: how is it that the earth ended up with this magic and nearly perfect temperature of 14C?
- Well, as you probably already know, it's radiation that determines this balance. The earth absorbs solar radiation from the sun, and it emits radiation back out into the blackness of the universe. So here's a question. If the earth were a simple black rock, absorbing solar radiation, and emitting radiation of its own, what do you think the temperature of the earth would be? Would it be 14C? Would it be warmer? Would it be colder?
- This is actually a question that was first asked and answered in the early 1800's, by a French scientist named Joseph Fourier. His answer was that the earth would be colder.



- To see how much colder, we can do our own calculation. This is the most math you'll see in this talk, so don't get too nervous. But it's interesting, so I'll walk you through it slowly.
- Here on the left is a schematic of the geometry of the situation. The earth is this tiny little dot, only 0.013 Mkm in diameter. The sun is 100 times bigger, 1.4 Mkm in diameter. And the distance from the earth to the sun is 100 times bigger still, about 150 Mkm. Both the sun and the earth are emitting electromagnetic radiation, but because the sun is much hotter, it emits much more.
- Now, this is something that Fourier didn't know when he did his calculation, but we know it now, so we can make use of it even if he couldn't. It turns out that the radiation an object emits, per unit surface area of the object, increases with temperature to the fourth power. This is called Stefan's Law, after a Serbian scientist named Jozef Stefan who lived in the late 1800's. This constant,  $\sigma$ , is called Stefan's constant.
- So the power radiating from the earth is Stefan's constant, times the temperature of the earth to the fourth power, times the surface area of the earth. How many of you know that the surface area of a sphere, like the earth, is  $4\pi$  times the radius of the sphere squared? For those of you who knew it, how many of you ever thought it would be useful to know?
- Now if everything is balanced, the power radiating from the earth must exactly equal the power radiating from the sun that hits the earth. So on the right side of this equation we have again Stefan's constant, times the temperature of the sun to the fourth power, times the surface area of the sun,  $4\pi$  times the radius of the sun squared. That's the total power radiating from the sun. But of course the sun is far away from the earth, and most of the power it radiates just goes into the blackness of the universe, not to the earth.
- To calculate how much does hit the earth, let's imagine erecting a gigantic sphere around the sun, so that the earth is embedded in the surface of that sphere. What would be the cross-sectional area of the earth as seen from the sun? Right, it's just the area of a circle with the earth's radius, and that is just  $\pi$  times the earth's radius squared. That's this factor in the numerator. And what would be the surface area of the huge imaginary sphere that the earth is embedded into? Right, it's  $4\pi$  times the distance from the earth to the sun squared. That's this factor in the denominator. The fraction of the power that the sun radiates that intercepts the earth is just the ratio between the two.
- So now we have this heat balance equation, and we can solve for the temperature of the earth. First, we rewrite the equation – cancelling the two  $\sigma$ 's, since they appear on both sides of the equation, and dividing the two sides by  $4\pi$  times the radius of the earth squared. Then, we plug in all of the astronomical constants: the temperature of the sun, 5780K, the radii of the earth, the sun, and of the imaginary sphere.
- The result is a predicted temperature for the earth of 279K, or 6C, or 43F. This is actually amazingly close to the actual temperature for the earth of 287K, or 14C, or 57F. But it is cooler by 8C, and to give you a sense for how big a difference this is, 6C is the average temperature of Stockholm, Sweden, while 14C is the average temperature here in Albuquerque. How many of you knew that Albuquerque actually has the average temperature of the earth!
- Of course, it isn't too surprising that this simple calculation is off. In fact, it probably ought to be off by much more than it is, because we have neglected some huge corrections. Interestingly, almost all of those huge corrections are due to one molecule. So here is a trick question. What molecule do you think that is?

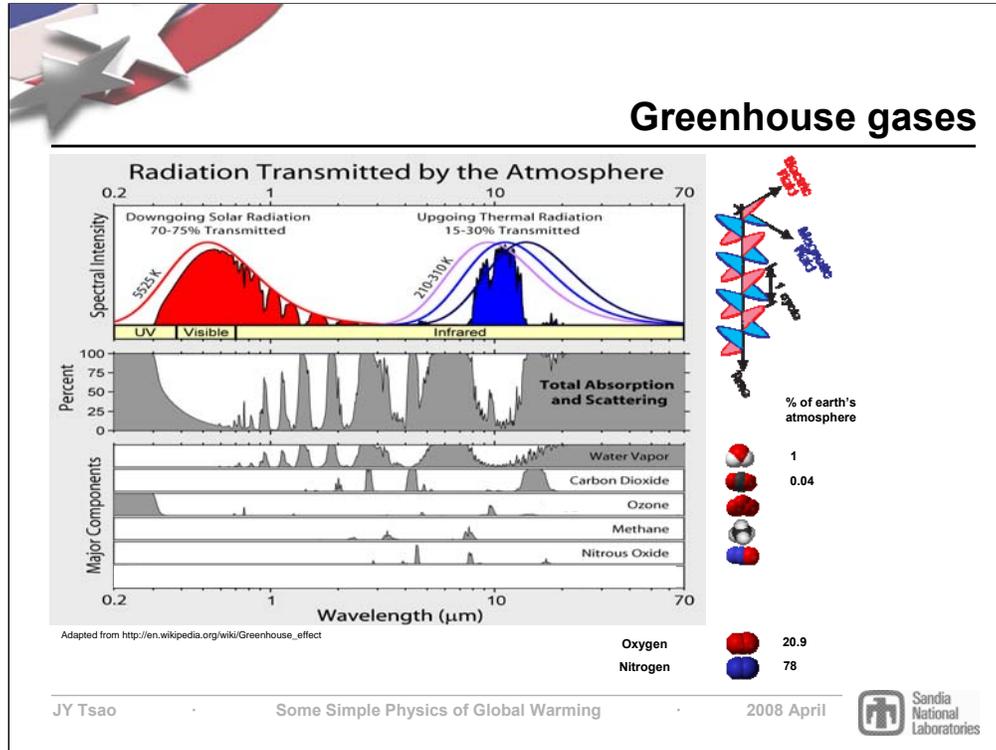
## H<sub>2</sub>O: Ice, Clouds, Water Vapor

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- No, it's not carbon dioxide, though of course that is indeed an important molecule. It's H<sub>2</sub>O, water.
- Here's a view of the earth from space. The features that really jump out at you are related to water: the blue oceans, the polar ice caps, the clouds. In fact, 30% of the sun's radiation that is intercepted by the earth is reflected, and much of that reflection is from the clouds, and from ice and snow. And 90% of the radiation from the earth is absorbed in the atmosphere, and much of that absorption is by clouds and water vapor.
- Not only does water itself modify the radiation balance and temperature of the earth, but if something else modifies the radiation balance and temperature of the earth, water can act as an amplifier. For example, suppose the earth warms up a little. Then some of the polar ice melts, and the earth reflects a bit less sunlight than before. Because more sunlight is now being absorbed by the earth, the earth warms up even more. Or, for example, if the earth warms up a little, then more water evaporates from the oceans. Then more of the earth's radiation is absorbed by water vapor in the atmosphere, and again the earth warms up even more.
- So water is the most important molecule modifying the radiation balance of the earth. We just don't think about it because we ourselves can't change it by too much. The concentration of water vapor in the atmosphere is determined mostly by evaporation from (and condensation into) the oceans, and the oceans are so massive that humans have very little direct effect on them. However, we note there are some examples where human have had some effect.
- Of course, after water, there are many other molecules that also alter the heat balance of the earth, particularly through absorption of radiation from the earth, and collectively these are called greenhouse gases.

## Greenhouse gases



- Here I show the most important of these greenhouse gases, along with their absorption spectra.
- The bottom axis of the figure is the wavelength of the electromagnetic radiation in micrometers, or microns.
- Some of you may know that visible light, light that the human eye can see, has wavelengths between 0.4 and 0.7 microns, exactly the wavelength range in which the sun's radiation is concentrated. That's no accident, of course -- our eyes evolved so as to be sensitive to the sun's radiation.
- Because the earth is much cooler than the sun, it emits infrared light, light that the human eye cannot see, at wavelengths between 8 and 20 microns. This is exactly the wavelength range which is absorbed by the various greenhouse gases. There's a narrow window at a wavelength of 10 microns through which some infrared light is transmitted, but by and large the rest is absorbed.
- As advertised, you can see that water vapor is the overwhelmingly most important greenhouse gas, mainly because it is such a large fraction, 1%, of the earth's atmosphere. Carbon dioxide is also important, but less so, mainly because it is a much smaller fraction, 0.04%, of the earth's atmosphere. Ozone, methane and nitrous oxide are also greenhouse gases, but there is much less of them still, and so they are correspondingly less important. Note, though, that methane, because it is so abundant in the earth, is also considered relatively important.
- Interestingly, the two molecules that are most abundant in the atmosphere, nitrogen at 78%, and oxygen at 20.9%, don't absorb in the infrared at all, and hence don't contribute to the greenhouse effect. So here's a slight digression, but an interesting one: why *don't* they absorb in the infrared?
- Let's start by asking why the other molecules *do* absorb in the infrared. Here I've sketched an infrared light wave – basically a rapidly oscillating electric and magnetic field that is traveling in space. We know that electric charges interact with electric fields – positive charges move one way and negative charges move the other way. But atoms and molecules usually have the same number of protons and electrons, so they are neutral, and don't interact as a whole with electric fields.
- But what if a molecule is composed of two or more different kinds of atoms. And what if the nuclei of the different atoms have a different propensity to attract electrons. Then, when the atoms form chemical bonds with each other, the electrons that are in those bonds might tend to be a little closer to one atom or the other. One atom might end up slightly negative, and the other atom slightly positive. Then, in an electric field, the slightly positive atom moves one way, and the slightly negative atom moves the other way, and the molecule begins to vibrate. This vibration represents an energy gain by the molecule, and an energy loss from the light wave.
- In fact, virtually all molecules composed of atoms that are different will have some internal charge imbalance, and will absorb infrared light. And even molecules composed of atoms that are the same but that see different local environments – like ozone with one oxygen atom at the center but two off to the side – will have some internal charge imbalance, and will absorb infrared light. But molecules that are composed of atoms that are the same and that have exactly the same local environments – like oxygen or nitrogen with two identical and symmetric atoms – have no internal charge imbalance, and won't absorb infrared light at all.
- Good thing, too, because if either nitrogen or oxygen absorbed infrared light, there's so much of them that the earth would undoubtedly end up being a furnace!



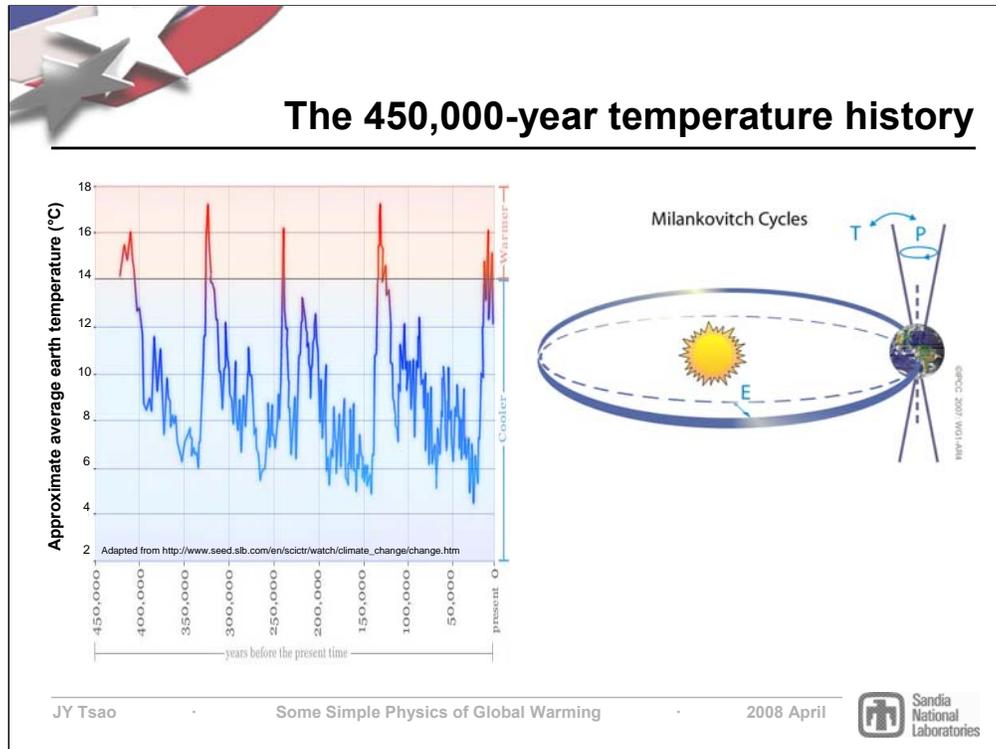
# Earth's Temperature History

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- So that's all I was planning to say about the earth's delicate heat balance. It's the balance between radiation in from the sun and out from the earth that determines the earth's temperature. And it's water that is the dominant molecule that alters that balance, by reflection and absorption. And then, after water, it's CO<sub>2</sub> that is the next dominant molecule.
- Before we go on, do you have any questions?
- OK, now let's talk about earth's temperature history.

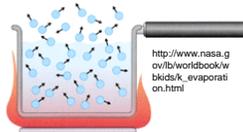


- Here I show the 450,000-year temperature history of the earth. These are the temperatures averaged over the entire earth, so parts of the earth will be much warmer than this, and parts will be much colder than this. So even though the current average temperature of the earth is about 14C, the temperature at the equator is about 30C, while the temperature in Antarctica is -50C.
- You'll notice that the earth has gone through cycles of warm and cold periods. We're right in the middle of a warm period right now. In fact, the irony of global warming is that, even though on a hundred year time scale we are headed for higher temperatures, on a 100,000 year time scale, we're actually heading for another ice age!
- You'll also notice that the cycles of warm and cold seem to occur just about every 100,000 years. Can anyone guess the explanation?
- Well, the current thinking is that it doesn't have to do with greenhouse gases, though greenhouse gases could certainly have amplified the effect. Instead, current thinking is that it has to do with the way the earth orbits around the sun.
- It turns out the earth's orbit around the sun is not a perfect circle; it's an ellipse. The ellipse isn't very eccentric – the distance between the earth and the sun only changes by about 3.4% over the course of a year – but it is nonetheless an ellipse. And in and of itself, there's nothing particularly interesting about an elliptical orbit – a small object can have an elliptical orbit around a large central object, and that orbit can be stable and never change. But, because of very small gravitational interactions with Saturn and Jupiter, the eccentricity of the earth's orbit changes over time – it gets bigger and then smaller with a periodicity of about 100,000 years.
- So when the earth's orbit is more elliptical, then, once a year, the earth gets slightly more sunlight, and we move into a warm age. And when the earth's orbit is more circular, the earth gets the same sunlight all year round, and we move into a cold age. Now, this idea was first put forth in the 1920's by another Serbian scientist, Milutin Milankovitch. But for 50 years his idea was pretty much dismissed. In part, the reason is that it was difficult to believe that such a small change in eccentricity could explain such large swings in temperature. Even now there is a lot of uncertainty. But there is a greater appreciation for how a small perturbation in temperature can be amplified, particularly by water.
- For example, if the summers are just cold enough that you don't melt the ice and snow from the previous winter, then ice and snow will suddenly begin to accumulate, the reflectivity of the earth will increase, and the earth will get even colder. So amplification makes it possible for these Milankovitch cycles to be the cause of the earth's various ice ages.

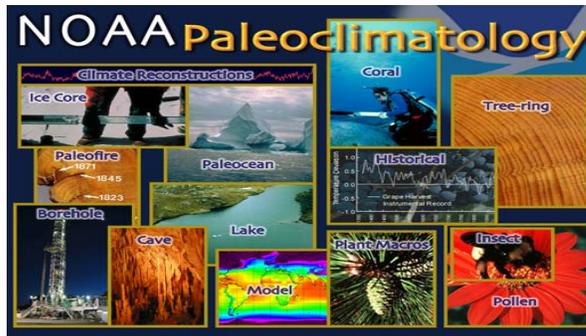
## The 1,000-year temperature and CO<sub>2</sub> history



Adapted from <http://www.koshland-science-museum.org/exhibitgci/images/historical03.gif>



The evaporation rate of the rare, heavy <sup>18</sup>O isotope of H<sub>2</sub>O is slower than that of the common, light <sup>16</sup>O isotope of H<sub>2</sub>O, and depends on temperature



National Oceanic and Atmospheric Administration (<http://wf.ndbc.noaa.gov/paleo/about-collage.html>)

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- Now let's move to the 1,000 year temperature history of the earth. Here we see that, indeed, from 1000 to 1900 there has been a general cooling trend, consistent with the idea that on a 100,000 year time scale we're heading into an ice age. But, suddenly, in the 1900's, the temperature starts to shoot up. And, at the same time, the concentration of carbon dioxide in the atmosphere also starts to shoot up.
- In fact, at this stage, there is a solid consensus amongst climate change scientists that these increases are real. One of the reasons for this consensus, I think, is because there are so many observations from so many different scientific disciplines and specialties. This figure is meant to illustrate that. There's the physics and chemistry of ice cores, there's the paleobiology of coral reefs and tree rings, and sophisticated paleoclimatology modeling. All of these observations appear to be consistent with each other, and whenever an observation appears to be inconsistent, further study is usually able to resolve the inconsistency. For example, not all ice core samples show the same record of temperature and carbon dioxide, but in the ones that don't, there's usually evidence that some geological event, like a glacier falling, has caused some portion of the ice core to be disturbed in some way.
- Speaking of ice cores, it's not hard to understand how carbon dioxide in gas bubbles might be trapped at various depths in the core, and thus to get a record of carbon dioxide concentration as a function of time. But how do scientists figure out temperature from these ice cores? Does anyone know?
- Well, I'll just mention one way, illustrated up at the top of this slide. As you know, many elements have isotopes. Oxygen is one of those. The usual isotope of oxygen has 8 protons and 8 neutrons, and so has a mass of 16 atomic units. But there is a reasonably abundant (0.2%) heavier isotope of oxygen that has 8 protons and 10 neutrons, with a mass of 18 atomic units.
- That means there are also two kinds of H<sub>2</sub>O molecules – one that is lighter, with O<sup>16</sup> in it, and one that is heavier, with O<sup>18</sup> in it. In the ocean, H<sub>2</sub>O molecules are constantly jiggling around, but the light ones jiggle a little faster than the heavy ones. So the light ones evaporate from the ocean just a little bit faster than the heavy ones, and the degree to which they evaporate faster depends on temperature. So the ratio between oxygen isotopes in the water in the air, and ultimately in the ice core formed from that water vapor, can be used as an indirect measure of temperature.
- So this sudden increase in temperature beginning in the 1900's looks to be real. Not only that, it looks to be different than previous warmings, which were determined by changes in solar radiation hitting the earth, amplified by water and other greenhouse gases like carbon dioxide. This looks like a change in one greenhouse gas, carbon dioxide, amplified by water and perhaps other greenhouse gases. In fact, at this stage, there is a growing consensus that this increase in carbon dioxide is caused by humans, and that at least part, if not all, of this increase in temperature is due to that carbon dioxide. Keep in mind, though, that the IPCC characterizes this as being *very likely*, meaning greater than 90% probability, but not certain.



# Earth's Sluggish Carbon Balance

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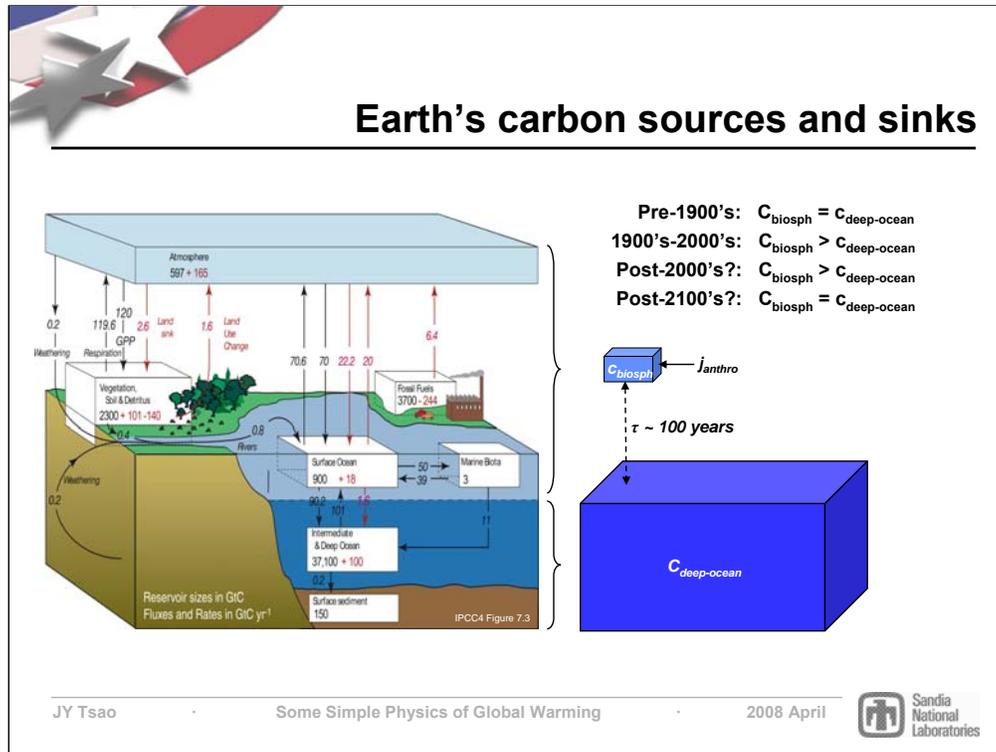
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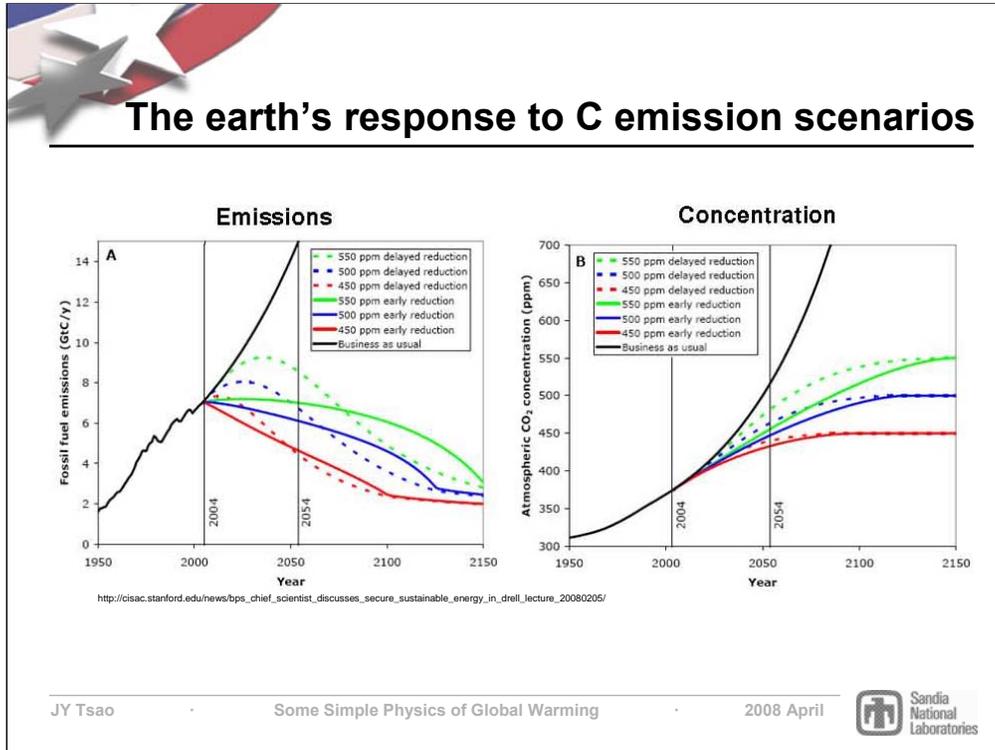
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- Nevertheless, very likely is still very likely, so for now let's assume that carbon dioxide is indeed the culprit. And if carbon dioxide is the culprit, then we need to understand its sources and sinks, and how those sources and sinks are balanced or imbalanced.



- So here I show an illustration of all of the various sources and sinks of carbon on earth. The black numbers are pre-industrial values, and the red numbers are post-industrial additions. So the atmosphere used to hold about 597 GtC, but now it holds an additional 165 GtC. The shallow ocean holds even more – pre-industrially about 900 GtC, and now an additional 18 GtC. Vegetation and soil holds yet more – pre-industrially about 2300 GtC, and now an additional 251 GtC. However, the biggest reservoir by far of carbon is the deep ocean – it holds more than 10 times all of the other reservoirs combined!
- In fact, if you lump the atmosphere, vegetation, and the shallow ocean into something we might call the biosphere – the part of the earth that biological systems interact closely with – then we have a picture that looks like this. There is a tiny biosphere, with a certain concentration of carbon, and then there is this huge deep ocean reservoir, also with a certain concentration of carbon.
- The rates at which carbon dioxide is exchanged within the biosphere are all relatively fast, so, at least on a 10-20 year time scale, we can treat the biosphere as one unit. But the rate at which carbon dioxide is exchanged between the biosphere and the deep ocean is very very slow. So slow that it takes about 100 years for the concentrations of carbon dioxide in the two reservoirs to come into equilibrium with each other.
- So, the sequence of events kind of looks like this.
- Pre-1900's, before we were dumping a lot of carbon dioxide into the atmosphere, there was plenty of time for the biosphere to come into equilibrium with the deep ocean. So the concentration of carbon dioxide in the biosphere was pretty much the same as the concentration of carbon dioxide in the deep ocean.
- In the 1900's and 2000's, we started dumping a significant amount of carbon dioxide into the biosphere. That means the concentration of carbon dioxide in the biosphere is now higher than the concentration of carbon dioxide in the deep oceans. Since all things want to flow from places of high concentration to places of low concentration, there is a net flow of carbon dioxide from the biosphere to the deep ocean. But the flow is tiny, because the exchange between the shallow and deep oceans is slow. So the concentration of carbon dioxide in the biosphere continues to build up.
- Post-2000's, if we were to suddenly stop dumping carbon dioxide into the atmosphere, then the concentration of carbon dioxide in the biosphere would stop increasing. And in fact it would start decreasing, as it tries to equilibrate with the deep ocean. But again because the exchange of carbon dioxide between the shallow and deep oceans is so slow, it would decrease very very slowly.
- It would only be post-2100's that, finally, the concentration of carbon dioxide might become "normal" again. But by that time, the earth's temperature would have gone through a significant cycle of warming.
- So this is one of the central problems of global warming, one that the public isn't all that aware of, but that has climate change scientists very nervous. There is *already* too much carbon dioxide in the biosphere, and because of the inertia of that carbon dioxide, even if we started reducing carbon dioxide emissions now, it would take a hundred years before we would recover.



- That's illustrated in these two graphs. The left graph shows CO<sub>2</sub> emissions, and the right graph shows CO<sub>2</sub> concentration, as a function of time.
- The business as usual scenario is in black, showing emissions continuing to increase past 2004, and concentrations also continuing to increase.
- The frightening curves are the colored ones, which show scenarios in which CO<sub>2</sub> emissions have been reduced significantly. Instead of tracking the CO<sub>2</sub> emissions reductions, the CO<sub>2</sub> concentrations actually continue to increase for a good 100 years, before beginning to roll over.

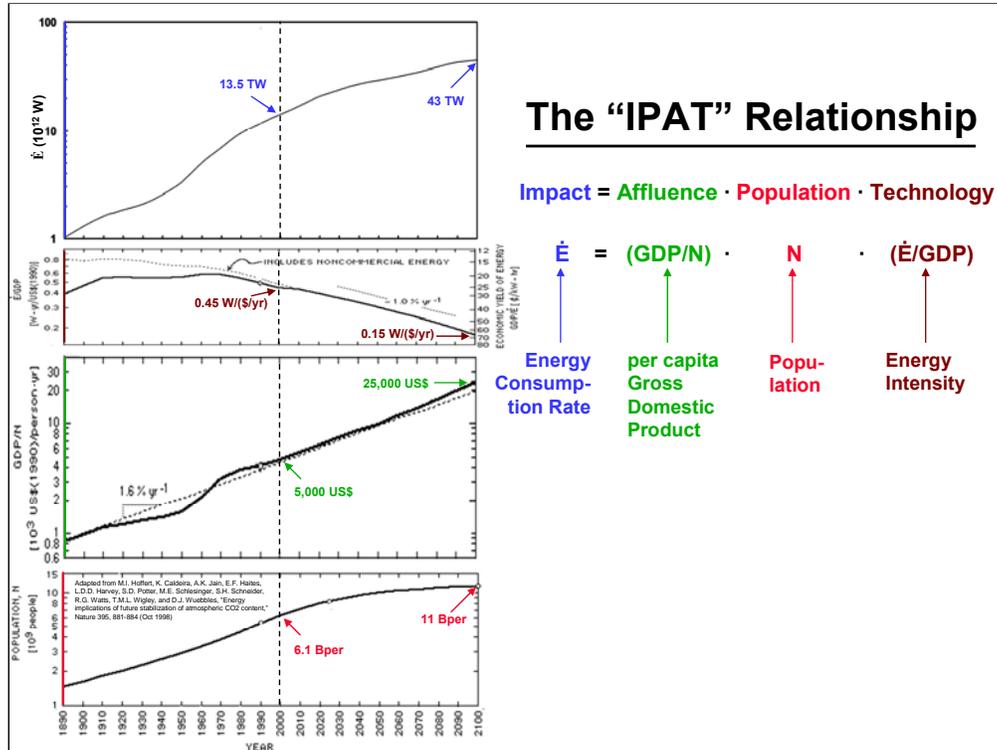


# Humanity's Appetite for Energy and Carbon

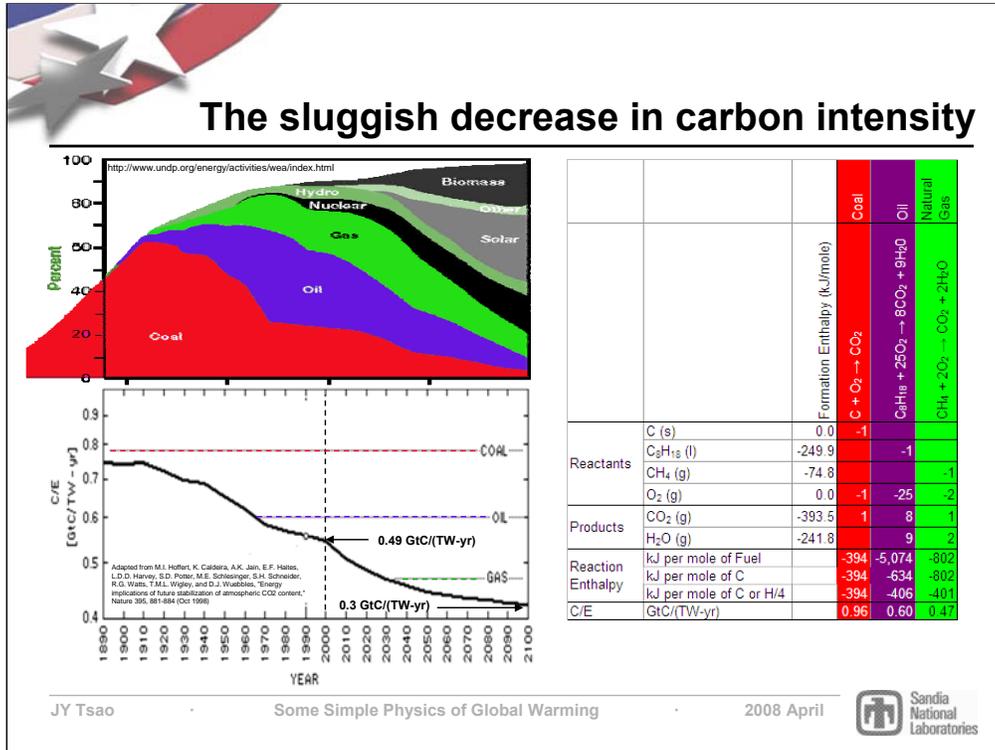
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- That doesn't mean we give up, of course. It's still better to reduce carbon dioxide emissions than not to reduce them.
- But that brings up yet another problem -- and that is that humanity has a tremendous appetite for energy, and the best ways we know to make energy involve also making carbon.
- Let's discuss each of those in turn.



- Here's an illustration of how it is that we consume so much energy. It's based on something energy economists call the IPAT relationship, which is that the impact of society on the environment is related to its affluence, its population, and its technology. In mathematical terms, it says that the rate at which a society consumes energy,  $\dot{E}$ , is the product of its population,  $N$ , its per capita gross domestic product (total gross domestic product divided by population), and something called energy intensity. Energy intensity is the amount of energy required to sustain a particular GDP – since we need energy to do just about anything, the higher the GDP, the more energy we consume.
- If you multiply all this out, of course, you just get  $\dot{E}$  is equal to  $\dot{E}$ . But breaking the various factors apart like this makes it easier to see what we're up against if we think about trying to decrease the energy consumption rate.
- In fact, all four of these quantities are plotted at the left, with historical data to the left of the dashed line, and projections to the right.
- Let's start with world population, at the bottom in red. Right now, world population is about 6 billion, and it's projected to grow to 11 or so billion by the year 2100. By that time, population is rolling over, because most of that growth is in the undeveloped worlds, and as they develop one can anticipate the same decrease in birth rate that has already occurred in the developed world. But, still, this is a significant increase. So here's a question: do you think it would be possible for us to avoid this increase in population?
- Now let's take per capita gross domestic product, here in green. Right now, per capita world GDP is about \$5K. That's projected to grow to \$25K by the year 2100. That's mostly the undeveloped world catching up to the developed world. The U.S. has a per capita GDP right now that's about \$40K, so even in the year 2100 the world will be less affluent than the U.S. is now. So here's another question: do you think it would be possible for us to avoid this increase in per capita GDP?
- Now let's take energy intensity, here in brown. Right now, we need about half a Watt of power to create a \$ per year of GDP. So the power from a 100W light bulb would be what you would need to generate \$200 per year of GDP. Of course, technology is constantly improving the efficiency with which we use energy, and as this happens, energy intensity decreases. In these projections, it goes down by a factor 3, to 0.15 W per \$/year of GDP.
- But it doesn't go down by enough to offset the increase in population, and the much larger increase in per capita GDP. When you multiply all of these factors together, you end up with an energy consumption rate that is about 13 TW right now (a terawatt is  $10^{12}$  watts), going up to 43 TW in 2100.
- So the bad news is that at an energy consumption rate of 13 TW, we are already putting too much carbon dioxide into the biosphere. And by 2100 our energy consumption rate will be 43 TW, and there is a good chance we may be putting in even more, rather than less, carbon dioxide into the biosphere!



- Ah, but there is one more factor that we haven't yet considered. It's called the carbon intensity, which is the amount of carbon we put into the biosphere per unit of energy that we consume. Different fuel sources have different energy and carbon contents, so to a certain extent we can reduce the carbon we create by switching fuels.
- That's shown in this bottom left figure, which shows the carbon intensity, in units of GtC/yr per TW of energy consumed. You can see that it has gone down from 0.75 in 1890 to 0.49 in 2000, and is projected to go down further, to 0.3, by 2100. The reason is that coal, which has the most carbon content of all of the fossil fuels (it's basically pure carbon) was by far the dominant fuel back in 1890. But, over time, oil, which has an intermediate carbon content (it's about one part carbon two parts hydrogen), has become more important. Natural gas, which has an even lower carbon content (one part carbon four parts hydrogen), has also become more important.
- By the way, one of way of understanding the carbon intensities of the various hydrocarbon fuels is the following. Hydrocarbons are by definition composed of carbon and hydrogen. Ultimately, when a hydrocarbon is burned (that is, oxidized by the oxygen in the air), you end up with two end-product molecules: carbon dioxide and water. It turns out that the bonds between carbon and oxygen in carbon dioxide are very strong, so a lot of energy is liberated when it is formed: about 400 kJ per mole of end-product CO<sub>2</sub> molecules (or, since there is one starting-reactant C atom per end-product CO<sub>2</sub> molecule, about 400 kJ per mole of starting-reactant C atoms). The bonds between hydrogen and oxygen in water aren't as strong, so less energy is liberated when water is formed: about 250 kJ per mole of end-product H<sub>2</sub>O molecules (or, since there are two starting-reactant H atoms per end-product H<sub>2</sub>O molecule, about 125 kJ per mole of starting-reactant H atoms). So each C atom in the fuel gives about four times more energy than each H atom in the fuel.
- This means you can just count the number of C or H atoms in the starting fuel, and figure out how much energy you will get. You get about 400 kJ per mole of C atoms, and per four moles of H atoms. Because CH<sub>4</sub> has one C atom and 4 H atoms, burning a molecule of CH<sub>4</sub> gives you twice the energy as burning an atom of C, but liberates the same amount of carbon dioxide. So the carbon intensity of natural gas, which is basically methane, or CH<sub>4</sub>, is just about exactly half that of coal. Oil, which is roughly CH<sub>2</sub>, is roughly halfway in between.
- But that means we've reached our limit with hydrocarbon fuels. Carbon can only make four bonds, so you can't attach any more hydrogens to carbon than four. So natural gas, or methane, has the highest ratio of hydrogen atoms to carbon atoms, hence the lowest carbon content per energy released, of any fossil fuel. So if we stick with fossil fuels, we'd be limited to this line here. The only way we are going to reduce carbon intensities even further is to switch to non-fossil fuels, such as nuclear, or hydro, or solar, or biomass. In these projections, these start to kick in in a big way around 2020 or so, and so the carbon intensity drops below that of natural gas.



# What can we do?

- **Plan A: Sequester the Carbon**
  
- **Plan B: Switch to Non-Fossil Fuels**
  - E.g., there is plenty of solar (an area the size of Venezuela could power the world)
  - But not economical yet, so need R&D *and* carbon tax
  - But a carbon tax could be a drag on GDP, unless it substitutes for income tax
  
- **Plan C: Climate Engineering**
  - Global gardening, atmospheric water/ice nucleation, earth albedo manipulation, ...
  
- **Plan D: Adapt to global warming**
  - Developed nations are the cause, but undeveloped countries are least able to afford to adapt
  - What is the cost of adapting, and who should pay?