A Global Warming Primer

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August 16, 2009

1 Carbon

Every week, I use about 40 liters of gas commuting. As well, my wife uses about 8 liters. Think about it: 48 liters, which weighs about 75 pounds, used to be buried underground and is now, because of our actions, dispersed in the atmosphere. Every week. In a year, that's 3300 pounds of carbon, or 12,000 pounds (6 tons) of CO_2, since each carbon atom from the gasoline is combined with two oxygen atoms from the air in combustion, and each oxygen atom weighs 1/3 more than each carbon atom. In fact, this is only about a quarter of our total carbon "footprint"; each of home fuel heating, airline flights, and food prepared for us add another 6 tons of CO_2. Total of 24 tons per year. Of course some of this can be divided by 3 as there are 3 persons in our household. So let's say 12 tons per person per year. That's a huge amount, and even so is quite a bit less compared to 20 tons per person, which is average for USA.

It's also not typical across the world. Western countries, especially North American ones, have habits that require extraordinary amounts of energy to feed. Commuting alone in large heavy vehicles great distances to their daily work, central heating, frequent airliner flights, fine food, etc. Average around the world is around 3.7 tons per person per year. Total: 25 billion tons per year. If you look up world population and CO_2 production, you will see it's ramped up significantly in the last 60 years. As a rough approximation, we use a linear ramp. In that case, the total production for all years is about 750 billion tons.

Why do I add up all contributions over many years? Good question. Carbon dioxide is a very stable gas. It does not break down in the atmosphere. It also has a very low vaporization point; much lower than any temperature on earth, so it does not precipitate out or come back to the ground in any other way. Some of it does come back to the oceans, but it is a very slow process; more on this later.

Now let's compare with the weight of the atmosphere. This is surprisingly easy to calculate. The average sea level air pressure is 14.7 pounds per square inch. That means the weight of the atmosphere above every square inch of earth's surface is 14.7 pounds. Multiply by the earth's surface area and we're done. Earth's area is 4π times the square of the radius, radius is 6400 km or 250 million inches. The result is 6 million billion tons (6 quadrillion, or in scientific notation, 6×10^{15}). Actually, a more accurate calculation taking into account the fact there's plenty of land above sea level, above which there is less than 14.7 psi, gives 5×10^{15}.

Now divide: 750 billion tons / 5 million billion tons = 150 per million, usually denoted 150 ppm, meaning 150 parts per million. Because CO_2 molecules are about 1.5 times heavier than average air molecules, the fraction of CO_2 molecules to air molecules is 100 ppm. Understand this is a very approximate calculation, but should be "in the ballpark" as physicists like to say, meaning it's not < 50 ppm and it's not > 200 ppm.

We can apply the same calculation to the amount of CO_2 we're adding each year: 25 billion tons / 5 million billion tons = 5 ppm by weight, 3 ppm by volume increase per year.

Now look at the measurements in Fig. 1. The red curve is measured directly, and the other 4 are measured from air bubbles embedded in ice cores that are dated by counting layers as with tree rings. For scientists, the reliability of these data is established by the fact that the different measurements agree well when they overlap, even though the measurements are from different parts of the world. (See Joos and Spahni (2007) for more detailed information concerning these data). Notice the stability over the last millennium, up to the point roughly where the industrial revolution started. Then it started rising dramatically and more and more rapidly. Currently it is rising at about 1.5 ppm per year, again, "in the ballpark" with the rough calculation above. (The factor of 2 difference is due to absorption by the oceans, as explained below.)

The increase since 1800 is about 100 ppm, and the observations and calculations above leave no doubt that the increase is anthropogenic. This increase is huge; 37%! CO_2 is naturally occurring and an essential part of life on earth. That anyone would question the importance of a 37% change away from the long-term average value, is to me quite inexplicable.

Since CO_2 is part of the natural "carbon cycle", and required for photosynthesis, one might hope that with the additional amount, the planet would become more lush by facilitating plant growth. In fact, just the opposite has happened. Because of deforestation, there

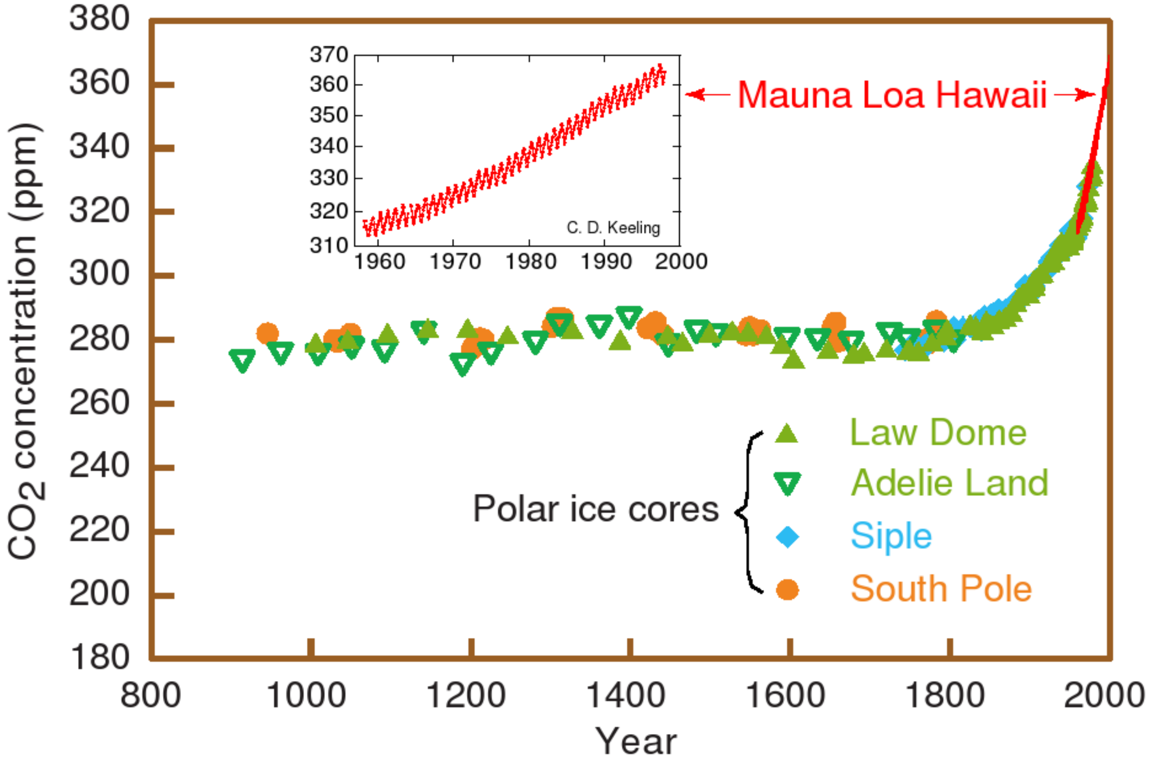

Figure 1: Global CO_2 over the last 1000 years. From Schwartz (2004), slide 7.

has been a decrease in vegetation on the planet, resulting in less carbon uptake. In other words, even without the burning of so-called “fossil fuels”, the CO_2 would have risen about half as much. This is indicated in Fig. 2 (blue curve).

Careful calculations find that the total additional CO_2 (green curve) is actually twice that measured. This indicates that only about half of the additional CO_2 remains in the atmosphere. Where does the rest go? Into the oceans. Though the additional uptake is not entirely understood, scientists are excited by it, because it suggests that perhaps by some process, we could sequester the extra CO_2, bringing the atmospheric concentration back down to normal levels. The oceans already contain 50 times more CO_2 than the atmosphere does, so it might be true that oceans can accommodate the little bit extra. But it does not look hopeful; see Doney and Levine (2006).

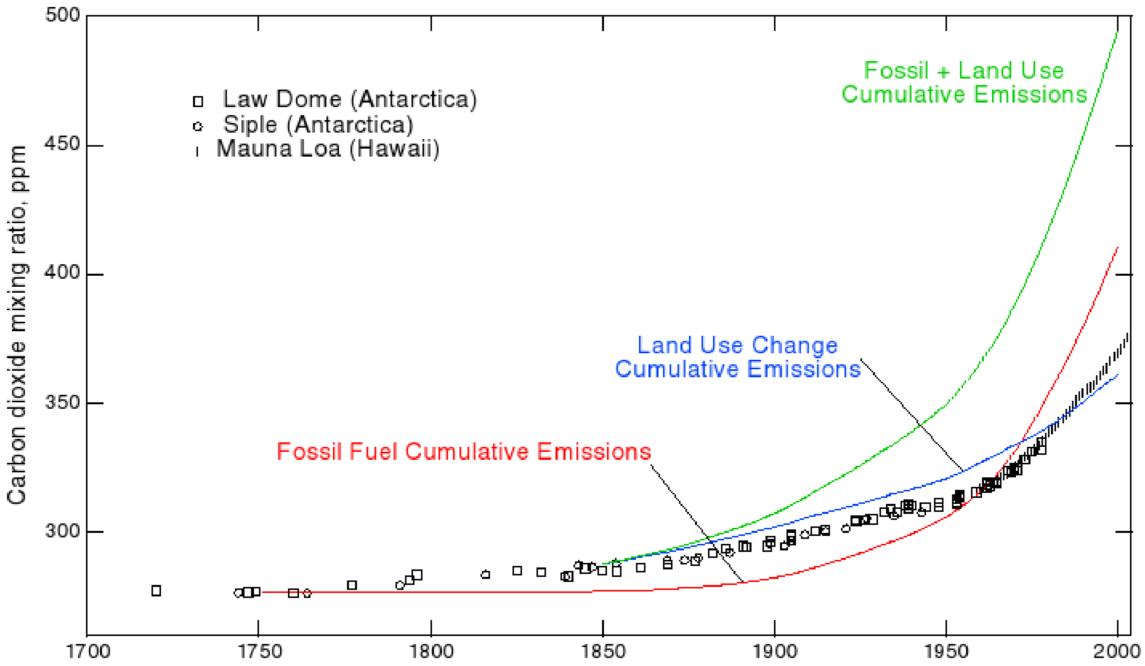

Figure 2: Atmospheric CO_2 and calculated anthropogenic contributions, over the last 300 years. From Schwartz (2004), slide 16.

2 Warming

When I was a child, I learned about the kinetic theory of gases and how temperatures of gases like air tended to even out. So it puzzled me why in the morning after a night of near-freezing temperature, there would be frost on the grass, but none under the picnic table. The reason is as follows. The grass "looks up" at the sky, so the radiation from the earth can move relatively unhindered out into space. At night, no radiation is coming back. The grass under the table releases the same radiation but it hits the table and re-radiates downward. It is for the same reason that in freezing weather, a thin sheet over the garden can protect it.

This effect is essentially the same as the "greenhouse effect". (It's a misnomer, though, as the effect is not the same as that which keeps greenhouses warmer. Greenhouses retain heat because there is no convection through the glass.) Up-going radiation can be absorbed by the gases in the atmosphere, and re-radiated downward. CO_2 is one of the gases with significant absorption in the infrared, as shown in Fig. 3 below.

What's meant by "infrared" radiation and how does it relate to heat? We know that colour relates to temperature. When we heat something sufficiently, we say it is red-hot. At higher temperature yet, it becomes white as all the colours of the rainbow are represented and these when mixed together form white. This is the same temperature as the surface of the sun. Heat it more and it becomes blue hot. At the other end, as something cools, it gets dimmer and dimmer red. In fact, the radiation is still moving beyond the colour red, but our eyes are not sensitive to anything beyond red. We call this "infra"-red. Heat radiation at room temperature has wavelength about 20 times longer than solar radiation as the sun is about 20 times hotter than room temperature.

Notice from Fig. 3 that the water vapour absorbs long wavelengths. This is the basis upon which microwave ovens work. (Confusingly, wavelengths about 1 cm are called "micro"-waves even though they are far longer than visible waves. The name arises from comparison to radio waves which are meters to km in length.)

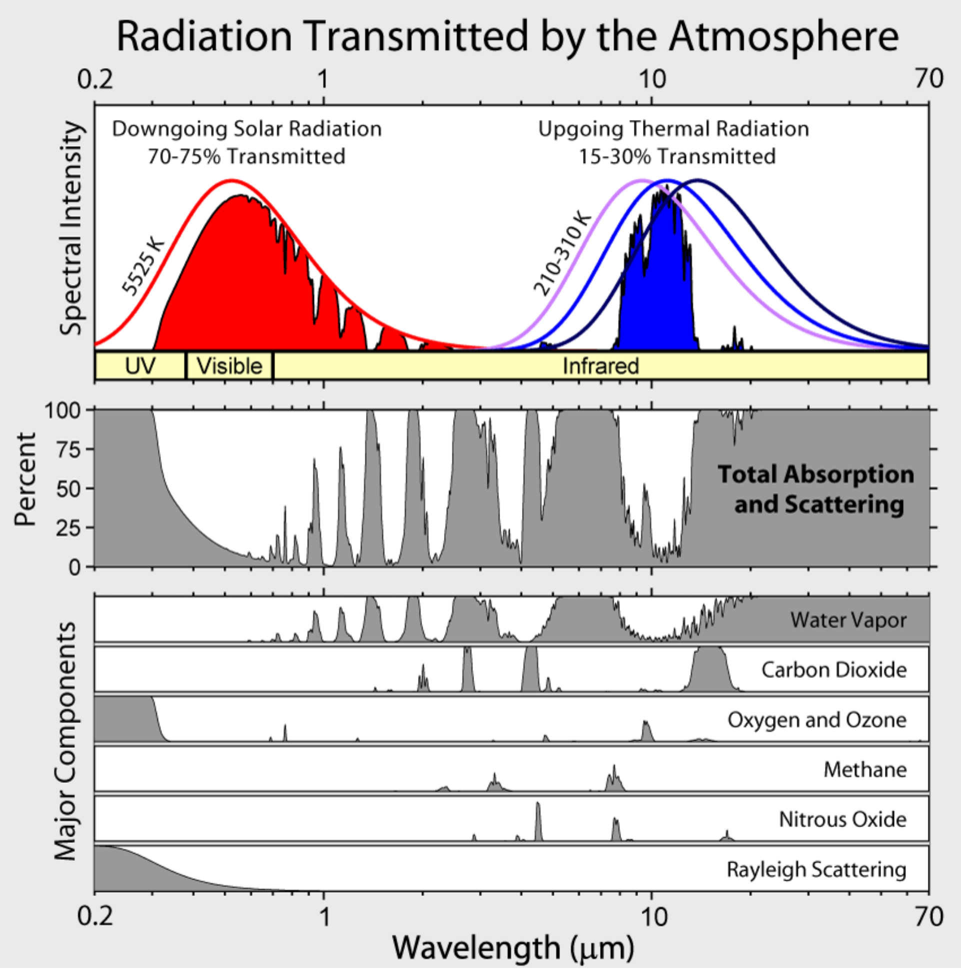

Figure 3: Radiation in (red) and out (blue) versus wavelength. Robert A. Rohde (2008).

To calculate the effect of the added CO_2, let's just take a very simple view. Refer to the

Fig. 3. If we took CO_2 out, the total greenhouse effect would reduce by 9%. Since spectra overlap, some of the absorption of radiation by CO_2 is taken over by water vapour. The total greenhouse effect is easy to calculate knowing the sun's brightness and the radiation laws from simple physics: If there were no atmosphere at all, the average earth temperature would be −18°C, not +14°C. This difference times 9% means CO_2 contributes 3°C to earth's temperature. Since the anthropogenic CO_2 component is 37%, the net global warming is 1°C. That wasn't so hard, was it?

Actually, it was a bit of a fluke. Besides CO_2, there are other effects that change the net amount of the sun's energy reaching earth, and all these other effects apparently nearly cancel each other. See Fig. 4.

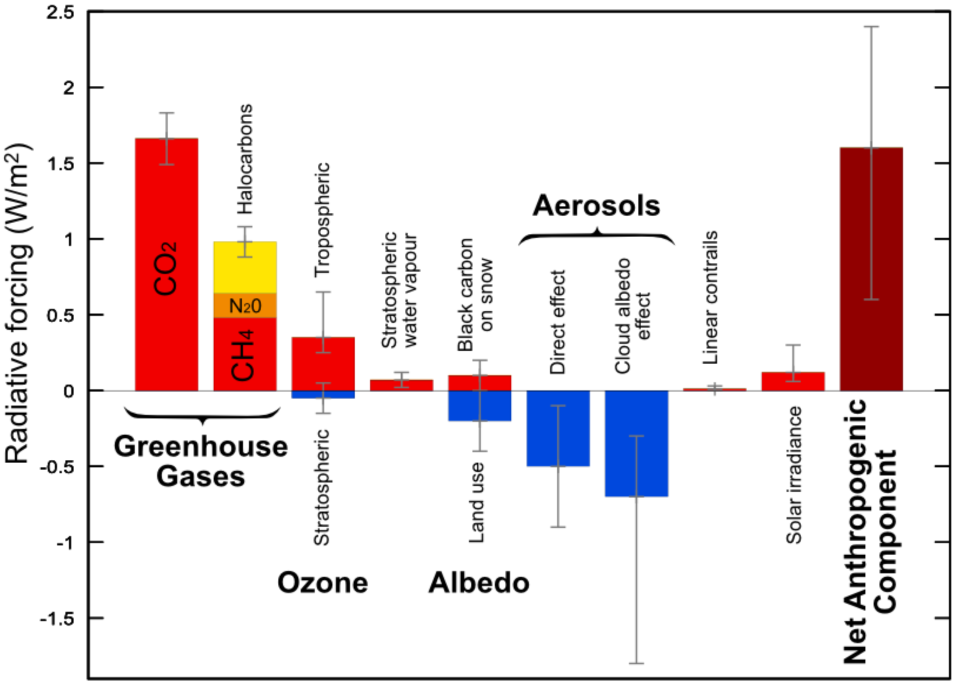

Figure 4: Radiative forcing components. The error bars are 90% confidence intervals. E.g. there is 90% confidence that the CO_2 component lies between 1.49 and 1.83 W/m^2. From the report: Intergovernmental Panel on Climate Change, 2007

Methane is also a significant contributor. Clouds, since they reflect sunlight, have a large cooling effect. Clearly, if our activities result in more cloud, we can offset the global warming. The amount of anthropogenic cloud creation is the hardest to calculate, as reflected in the very large error bar in the Fig. 4. Because of the cloud uncertainty, the total calculated effect has a 90% probability range of a factor of 4. In other words, our 1°C calculated could with 5% probability be < 0.5°C and could also, with 5% probability be > 2°C. Nobody is happy with this level of uncertainty (except of course those who love to point out that scientists don't know what they're talking about).

3 Measurements

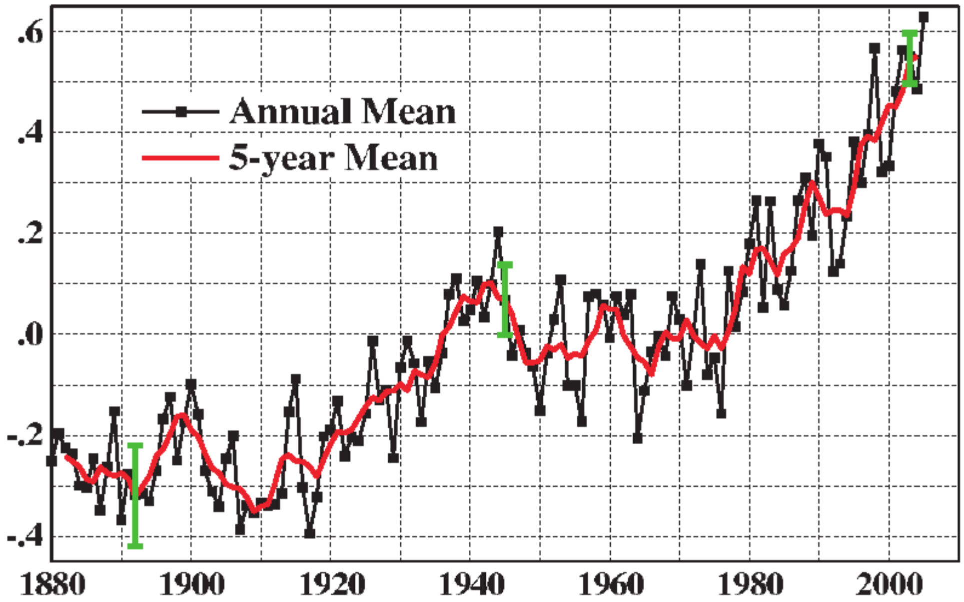

Figure 5: Surface temperature change with respect to average of 1951-1980. Data are from weather stations, ships, and satellites observing sea surface. From Hansen et al. (2006).

Weather is variable. Last month here (July 2009, Vancouver) we went from a heat wave to very cool, a change of almost 20°C, in the space of a few days. So how would one detect something as small as a 1°C effect? Clearly, one needs to average, not just over many years, but also over many locations. That's what the graph (Fig. 5) shows. 1°C rise since the start of the industrial revolution looks to be in quite good agreement with these data.

In spite of the "noise" in the data, there are a few features that can be investigated. What happened just after WWII, where the temperature dropped and then appeared to stabilize? This is due to industrial ramp-up. Without any controls, the aerosol pollution produced (mostly sulfates) counteracted the extra CO_2. By the 60s, it was discovered that the sulfates were causing "acid rain", killing life in rivers, lakes, and killing whole forests. Sulfates cause global cooling by reflecting incoming sunlight. After the "clean air act" legislation, sulfates began to decrease while CO_2 emissions continued to rise. Streams and lakes have recovered quite nicely (a good-news story no one reports because after all, who cares about good news?), but now warming became a problem.

In 1988, when climate models were not nearly as well-developed as now, James Hansen was sufficiently worried that in congressional testimony, he presented the graph in Fig. 6. Note that the new data from 1988 to 2005 follows scenario B quite closely. Randomly, he picked 1995 as the year of a major volcanic eruption (note the dip in the blue curve). In fact, there was a major eruption, Pinatubo in 1991, so the black and red curves are below the blue curve from 1991 to 1995.

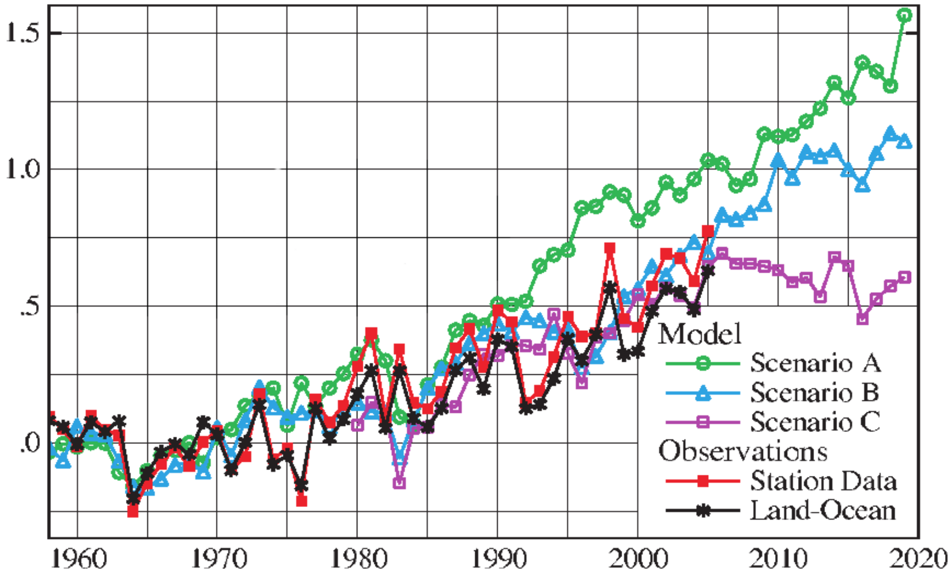

Figure 6: Global surface temperature modeled (Scenarios A, B, C), and measured (red, black). This was presented in 1988; at that time of course the black and red curves extended only to 1988. From Hansen et al. (2006).

Note that the globally averaged data fluctuate year to year by 0.2°C. Even the 5-year running average jumps around by 0.1°C. The long-term average slope is 0.02°C per year. It is utterly futile to pick this rate out of a 10-year data window, as some journalists try to do.

Year to year local measurements are of course much worse. I wanted to check the data for myself, so went to the station data website. There, you can click on a world map and it will list the weather stations nearby. Pick a station that has records from about 100 years back, to the present day. I picked Clearbrook (near Vancouver). See Fig. 7. Notice that year to year fluctuation can be as large as 2°C! One hundred times the change expected from global warming! So claims that an unusually cold winter indicates that there is no global warming are clearly specious.

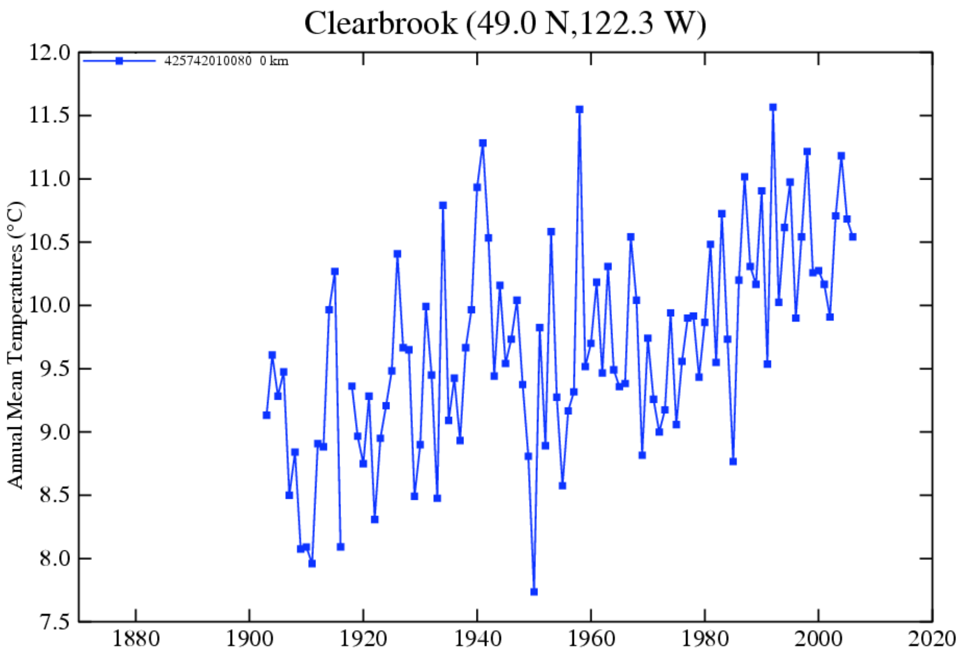

Figure 7: Annual mean surface temperature for Clearbrook, BC. From the NASA Goddard Institute for Space Studies

4 Effects

So who cares about a measly 1°C? We can have hot years, cold years, in one particular weather station, the average temperature through the year can differ by 3°C from one year to the next, as shown in Fig. 7. Why worry? Because there are large effects that depend upon long-term average temperatures.

One such effect is rising sea level. Measurements indicate the sea has risen 20 cm over the past 100 years.

Another effect is permafrost melting. To investigate this, I used the station data website to find average temperature as a function of latitude North. It turns out that where the average is near 0°C, it drops by about 1°C for every 1° North, which is about 110 km. If the world has warmed by 1°C, then the permafrost edge should have moved about this distance North. Then I found Kwong and Gan (1994). Their measurements indicate the edge has moved 120 km. Seems like a real effect!

5 Conclusions

1. Measurements indicate that the CO_2 level in the atmosphere is rising at an unprecedented rate. Simple calculations confirm that the increase is anthropogenic.
2. Earth's temperature rises with atmospheric CO_2. The physics of this effect is well-understood.
3. The observed temperature rise is consistent with the observed increase in atmospheric CO_2 concentration.
4. The temperature rise is causing global changes.