The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

The Carbon Economy

Posted by Stuart Staniford on January 30, 2006 - 4:15am
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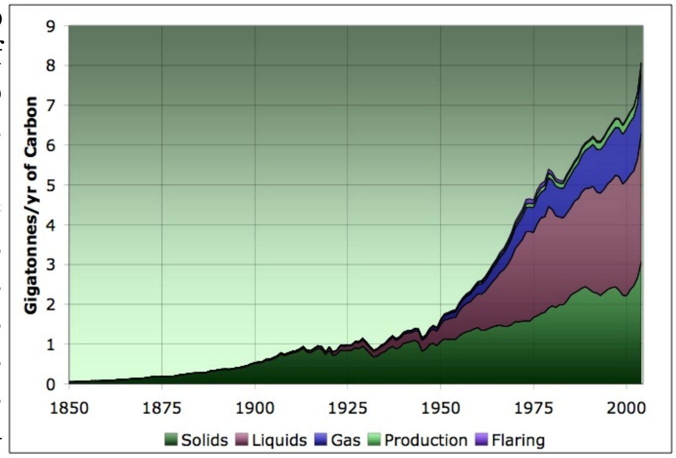
Tags: biofuel, carbon cycle, climate change, global warming, hubbert peak, kyoto, oil prices, peak oil [list all tags]



One of my goals in my peak oil studies is to understand the whole system of planet+economy as best I can. I want to develop an informed opinion on what humanity's options are as it faces these interlocking crises-in-the-making. That's obviously an enormous task. The relevant disciplines include at least geology, petroleum engineering, economics, sociology, urban planning, international development, climatology, demography, political science, mining engineering, military strategy, archaeology, history, chemistry and chemical engineering, physics, statistics, biology, ecology, agricultural science, and electrical engineering. No-one can hope to master all these subjects to the point a specialist in them would know them.

And yet it seems to me that, while accepting this limitation, it's worthwhile for a few generalists such as myself to attempt to try to understand the situation as deeply as possible in all aspects; it may be that new ideas and insights can only come from deeply integrating a number of the important perspectives. Only time will tell.

In that spirit, I'm trying to understand the carbon cycle and in particular the current carbon flows in the economy. I have two goals - one is to better understand the debate over the viability of biofuels. The other is to better understand whether we have any real options over climate change other than just suffering the consequences of our collective fecklessness. Either way, I can never make any sense out of any debate like this until I start to understand the relative sizes of the flows involved, and the trends in them.

This post is the first in a series of (so far) four on the carbon cycle and carbon in the economy which I'll be putting out one per day this week (if I can finish them fast enough anyway).

Let's start by looking at the overall planetary carbon cycle, which is summarized in a nice graphic from the Wikipedia. (I also recommend the more detailed version in the 2001 IPCC report).

Earth's carbon cycle with stocks in Gt (Gigatonnes), and flows in Gigatonnes/year. Click to enlarge. Source: Wikipedia. Click to enlarge.

The black text represent the stocks of carbon in the system in gigatons (billions of metric tons/tonnes). To give you a feel, one gigaton of carbon is the amount of carbon in about 8-9 gigabarrels of oil. So when the world is currently producing about 30 Gb a year of oil, that is a little less than 3.5 Gt of carbon (just in the oil), most of which is released into the atmosphere in the form of CO_2. (However, the quoted weight is just that of the carbon in the CO_2, not the oxygen chemically bonded to it).

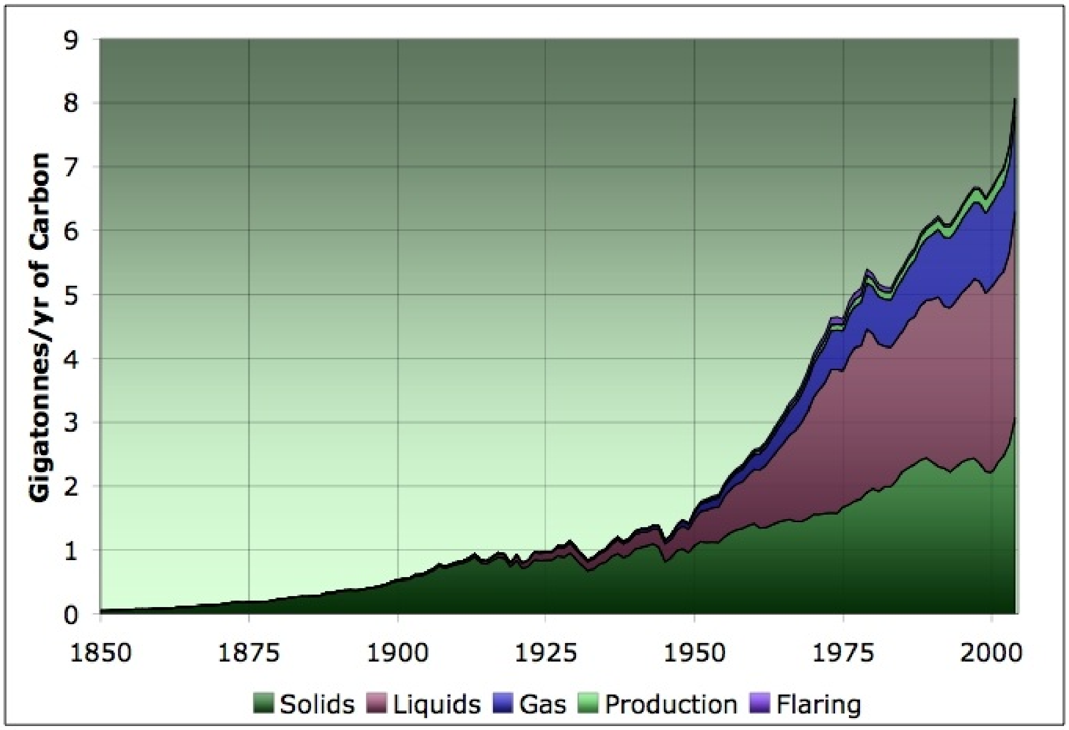
There are 750 Gigatons of carbon in the atmosphere, an enormous 39000 Gt or so in the ocean, about 610 Gt in vegetation, and another 1580 Gt in soils. Finally, there is a huge amount in the earth's crust.

Actually, the atmosphere is likely up to about 800 Gt now - the Wikipedia's numbers are a little out of date in this and a couple of other respects, as we'll see.

Anyway, the purple lines and numbers represent the flows in the system. We'll focus on the flows in and out of the atmosphere, as that's where our big problem is. Carbon leaves the atmosphere through two main routes, the ocean, and vegetation. The ocean exchanges about 90 Gt/year with the air, but there's a net sink of about 2 Gt/year. This is because humans have increased the CO2 concentration in the air, the ocean is not in equilibrium with it, and there's a net flow into the ocean (which should increase further as atmospheric concentration goes up further).

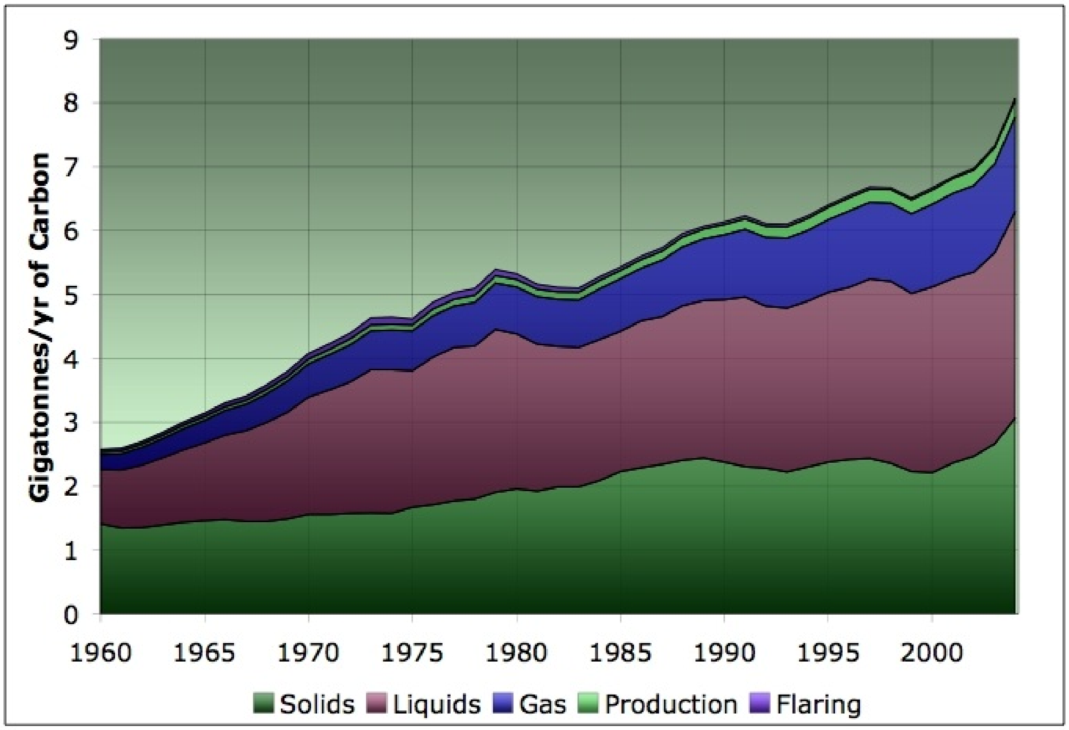
More interesting is the exchange with the biosphere. Plants absorb about 120 Gt of carbon/year and turn it into sugars via photosynthesis (and then onto other materials). This is the *gross primary production* of photosynthesis in the biosphere. Of this, the plants themselves burn about 60 Gt of carbon (in the form of sugars) to power their own operations, so that is released out into the atmosphere again immediately. The remaining 60Gt or so is called the *net primary production*. Almost all of the net primary production ends up going into the soil (a small amount passing through some animal on the way), but humans use and burn some of it. The soil releases back pretty much all of the carbon influx through the action of decay organisms. The (biosphere+soil) system as a whole is pretty much in equilibrium with the atmosphere, but not quite. According to the 2001 IPCC report), there is a net release overall of 0.2Gt/yr of carbon from the (biosphere+soil) because of the actions of humans (but there has been considerable uncertainty on this issue historically). Again, these numbers are a little out of date (more below).

Since 610 Gt is stored in the biosphere, about 20% of the carbon there turns over annually - this represents a weighted average of annual crops and weeds together with redwood and bristlecone pine tree trunks. The main net flow into the atmosphere is that 5.5 Gt/year in fossil fuel burning that the Wikipedia has. However, this next graph contains more accurate information with the trend over time:



Carbon emissions in Gt/year 1850-2004. Click to enlarge. Source: [ORNL] through 2002. 2003-2004 were estimated by scaling the 2002 numbers by the appropriate percentage increases in coal, oil, and natural gas from the [BP annual production numbers].

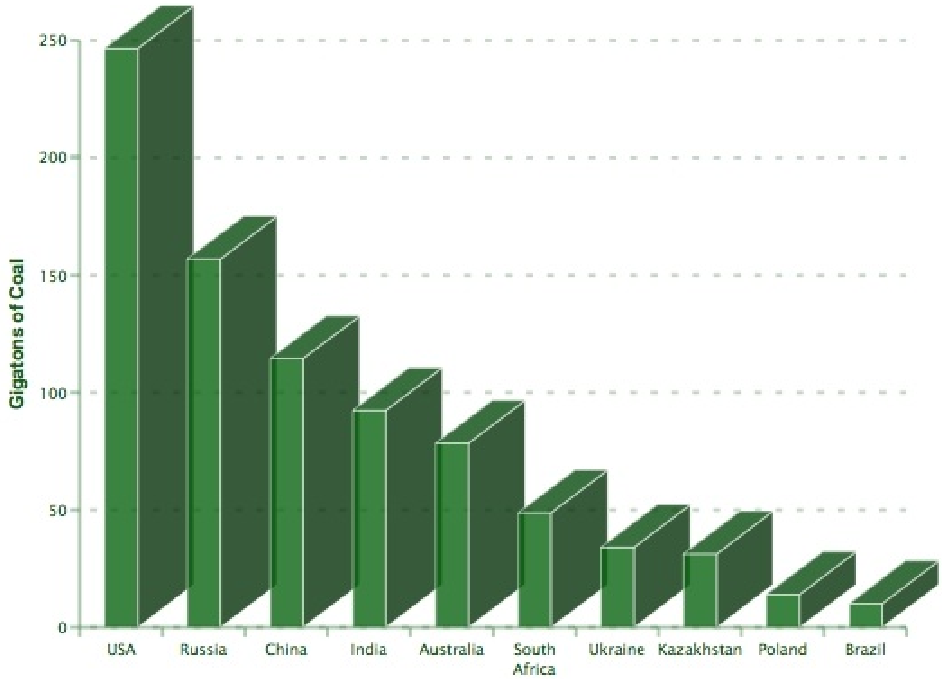
As you can see, we are at 8Gt/year now, and climbing fast. I started with this graph that goes back all the way to 1850 so you can get a sense for how much of the emissions have been since 1950. I also want to draw attention to the fact that this net flow is not yet enormous compared to the exchanges in the system - eg it's significantly smaller than the 120 Gt that runs through the biosphere each year (although as we shall see, it's quite a bit larger than the amount of carbon entering the economy from the biosphere currently). Let's now focus in just on the timeframe since 1960:



Carbon emissions in Gt/year 1960-2004. Click to enlarge. Source: [ORNL] through 2002. 2003-2004 were estimated by scaling the 2002 numbers by the appropriate percentage increases in coal, oil, and natural gas from the [BP annual production numbers].

The big uptick in Chinese coal production is very clear after 2000, and the big run-up in oil production from 2002-mid 2005 adds to it. As you can see, the implementation of the Kyoto protocol is not having a dramatic effect on the overall world emissions yet - the trend is going exactly in the other direction. We'll take up Kyoto further in a future post.

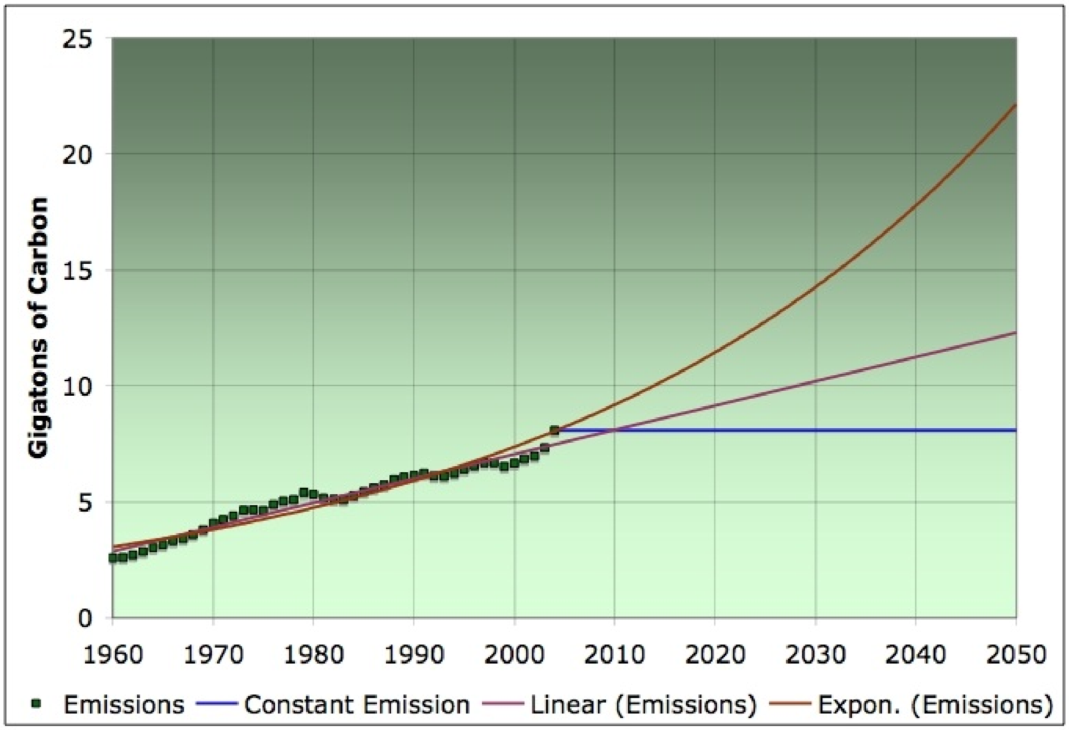
Before we move onto looking at how much impact this has on the atmosphere, let's briefly discuss how we might extrapolate this into the future. Obviously, peak oil is going to have an effect on the oil piece of the picture. However, since I currently favor the slow squeeze idea, I think that, while there might be a significant transitional reduction in carbon emissions due to peak oil, over the decades-long timescale we'll see the carbon emissions continue to grow. Initially, natural gas will take up some slack, but the big issue is this:



Ten countries with the largest 2004 coal reserves, in Gt of coal. Click to enlarge. Source: BP.

As you can see, with 1000 Gt of coal reserves (which is probably somewhere in the range of 600-800 Gt of carbon), we can keep up a high rate of emissions for a long time to come. And then there's the tar sands, Orinoco belt oil, oil shale, 3000 Gt of coal under the North Sea, etc. These sources are capital intensive, so they cannot be exploited quickly. But slow declines in oil production will allow them to be brought online as alternatives. And at a minimum, I think we have to assume that the Chinese can keep up a healthy rate of growth in their coal production (running at 10% annually recently). Furthermore, to the extent coal displaces oil, coal has more carbon per Joule of energy than oil. As many of us have studied, energy usage is very price inelastic and tends to have income elasticity close to one - so it grows with GDP and it takes an awful lot of price to change it much. Similarly, this inelasticity corresponds to enormous political resistance to reducing fossil fuel usage.

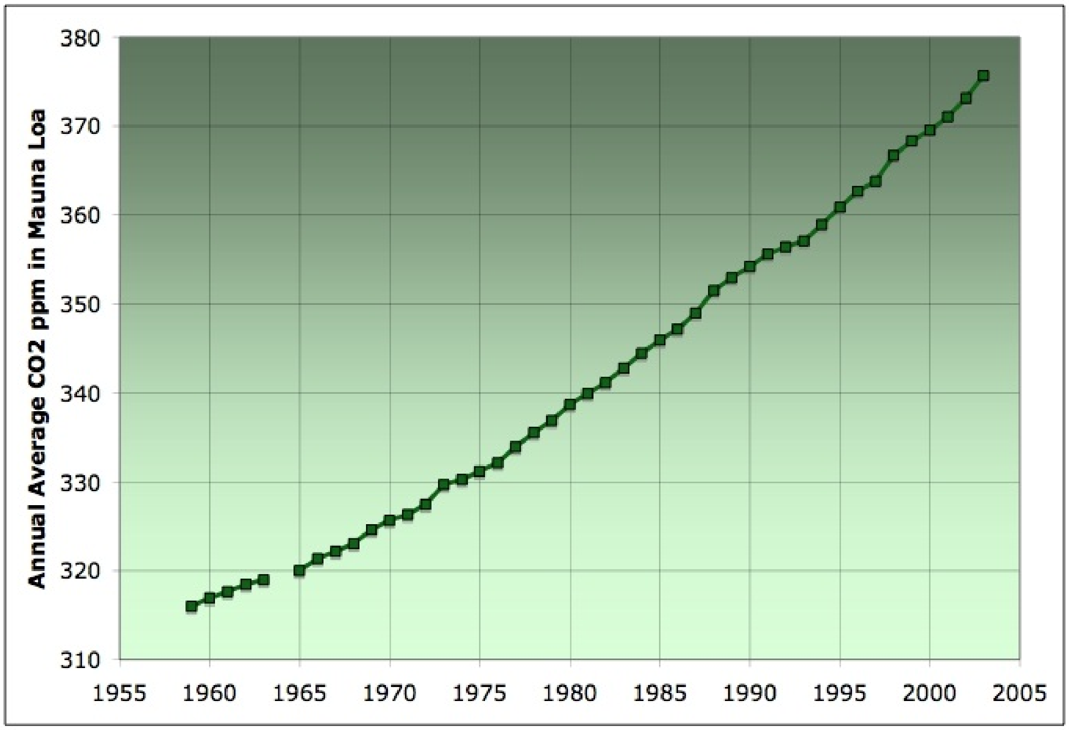
All in all, keeping it simple, I'm just going to assume that we can linearly extrapolate the trend of the last 45 years into the future for a "business-as-usual" scenario where the world make no effective attempt at emissions control. I've also put in an exponential extrapolation, and the line that would happen if the world could keep fossil fuel emissions constant at the 2004 value.



Carbon emissions in Gt/year 1960-2004, together with linear, exponential, and constant extrapolations through 2050. Click to enlarge. Source: [ORNL] through 2002. 2003-2004 were estimated by scaling the 2002 numbers by the appropriate percentage increases in coal, oil, and natural gas from the [BP annual production numbers].

Obviously, there is a great deal of uncertainty here, but the linear extrapolation is probably as good as any other. At any rate, the area under that purple curve is significantly less than the world's existing coal reserves alone, never mind the alternative hydrocarbons. So there's no physical barrier to humanity releasing this much carbon. The exponential curve would use up all the existing reserves of coal by 2050, so we'd be mining for coal under the ocean. Hence it's probably a very generous upper bound on what the economy could actually do. Similarly, the constant (blue) line seems quite hard to square with the implications of Chinese cement production. The global economy is not on track to control emissions like this any time soon.

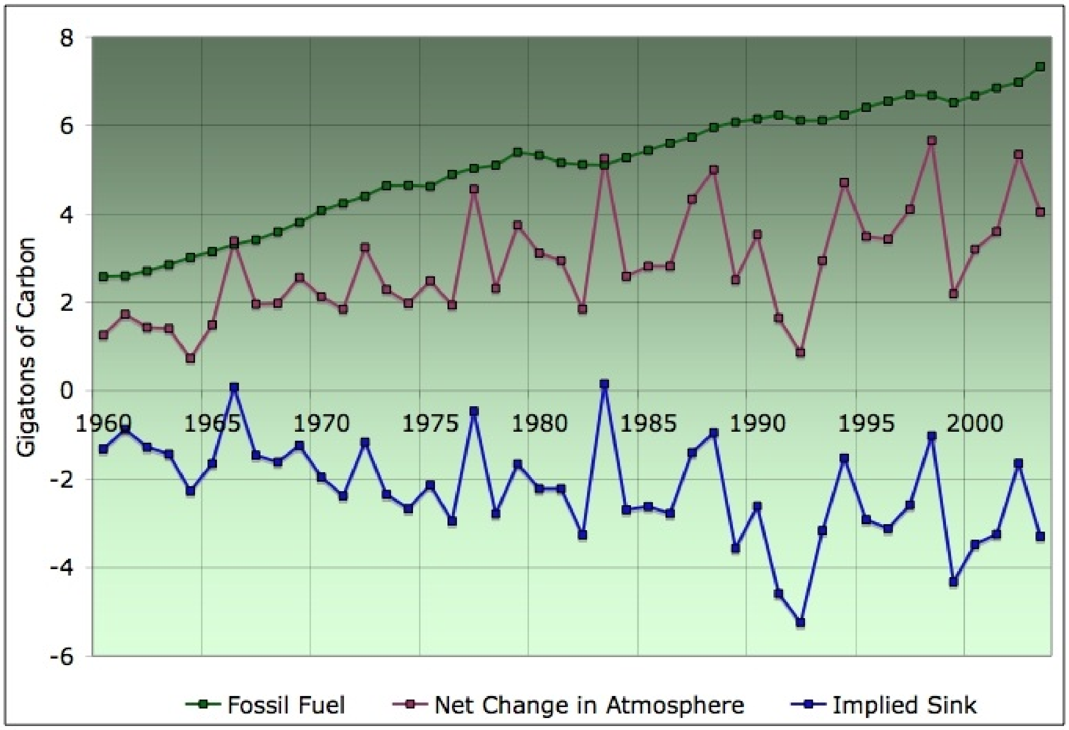
The effect of burning this stuff is as follows:



Annual average concentration of CO_2 in the atmosphere since 1959 as measured by Keeling et al in Mauna Loa, Hawaii. Graph is not zero-scaled. Click to enlarge. Source: Keeling via ORNL.

Now, the mass of the atmosphere, according to the Wikipedia again is 5.1 million gigatons, and almost all of that is well-mixed on the relevant timescales. So we can take those measured percentages, and convert them into a net uptake of carbon by the atmosphere. (If any reader should decide to check my calculations here, remember that the ppm numbers are by volume, and you have to correct for CO_2 having higher molecular weight than the other species in the atmosphere, and you only want the tonnage of carbon, not CO_2).

So then I get this graph. The green line is the fossil carbon emissions, the plum line is the net addition to the atmosphere according to the CO_2 measurements, and the blue line is inferred difference - the sink of CO_2 because the atmosphere is out of equilibrium with the other components of the system (together, possibly, with any net effect of humans on the biosphere).



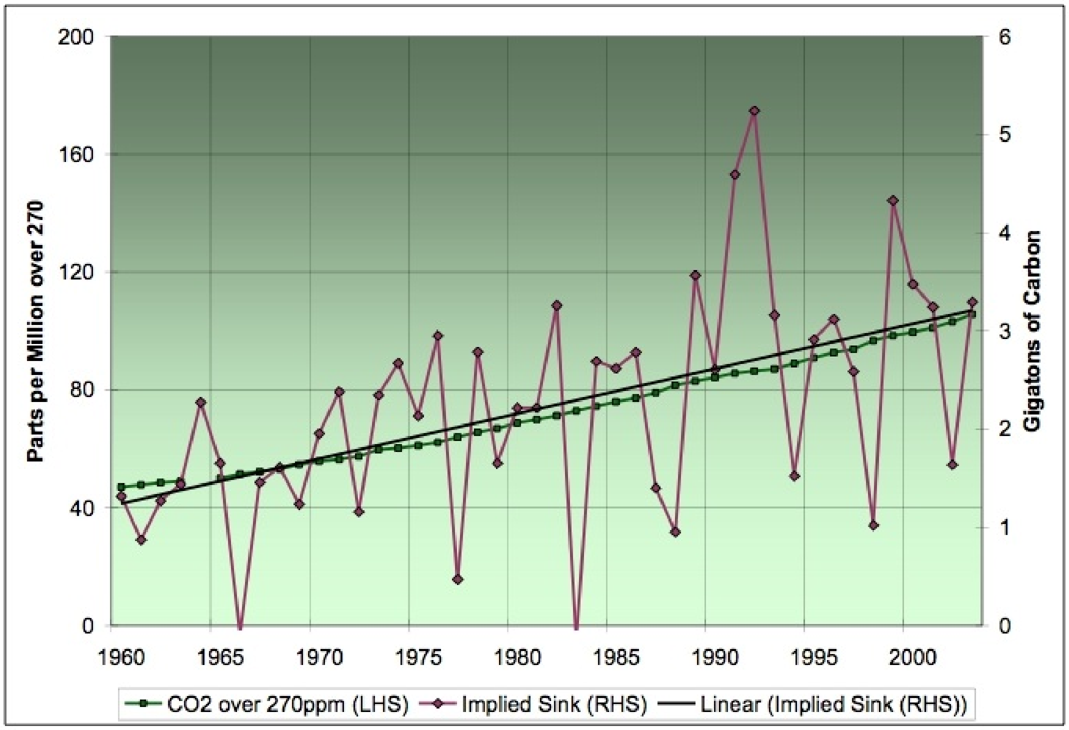
Carbon emissions in Gt/year 1960-2004, together with net increase in carbon in the atmosphere, and the implied "sink" of carbon via all other processes. Click to enlarge. Source: carbon emissions from ORNL through 2002. 2003-2004 were estimated by scaling the 2002 numbers by the appropriate percentage increases in coal, oil, and natural gas from the BP annual production numbers. Annual average concentration of CO_2 in the atmosphere as measured by Keeling et al in Mauna Loa, Hawaii via ORNL.

Notice that the sink is a significant offsetter of the fossil fuel emissions, but is quite volatile year-to-year. This makes sense if you think about the fact that there's big exchanges in the system. *Eg*. 120 Gt/year of carbon fixation by plants is offset by a similar amount of carbon release due to respiration by plants, animals, and microorganisms in the soil. It doesn't seem hard to believe that fluctuations in weather, etc, could cause that system to be different than its average by a few percent either way in any given year. Likewise, CO_2 exchange with the ocean must involve deep upwelling waters with low concentrations of CO_2 taking on more carbon, and CO_2 rich water giving up carbon to winds that had crossed rural areas and lost carbon to plants. The vagaries of currents and weather could cause significant fluctuations in this also.

In the graph, it rather looks to me as though the overall volatility in the absorption of CO_2 is increasing over time.

Now this net sink of carbon has spawned an enormous scientific literature trying to measure, study, model, and project it. I am going to cheerfully short-circuit that literature and develop a simple planetary-engineering rule-of-thumb for it instead. I hypothesize overall that the annual sink of carbon into the non-atmosphere components of the system should be roughly proportional to the difference between the current atmospheric concentration of CO_2 and the pre-industrial value for CO_2. This is because that flow represents the atmosphere re-equilibriating with slowly-changing components of the system, such as the ocean (which takes O(1000yr) to turn over), tree trunks, deep layers of soil, etc.

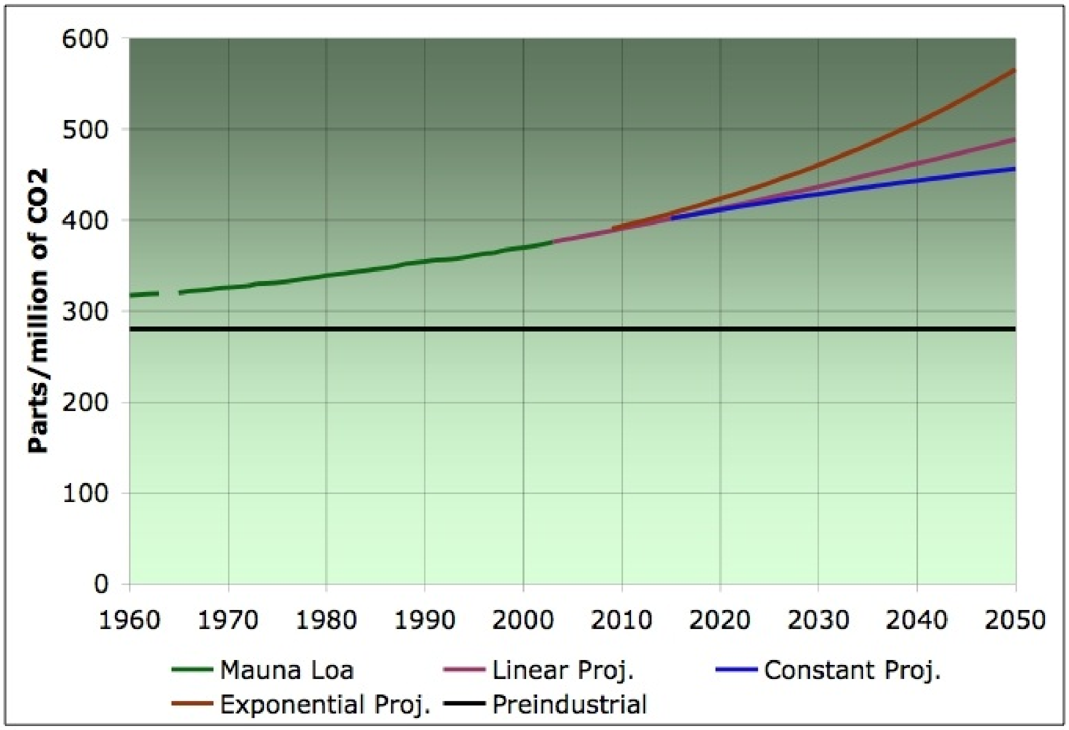
If we plot the annual sink of carbon versus the excess of CO_2concentration over and above 270ppm (which gives a slightly better fit than the generally accepted value of 280ppm), we get:



Excess of annual average concentration of CO_2 above 270ppm (left scale), and inferred annual sink of carbon in Gt/year (right scale). Click to enlarge.

The annual sink value, although noisy, has a definite linear trend to it (eg a quadratic fit lies very close to the linear fit), and when plotted on suitable scales, the two align nicely. This suggests that for every 100ppm additional of CO_2, we will get another 3 Gt/year of additional sink. Now, no doubt this linearity will break down at some point. Thus the extrapolation, like all extrapolations, has its dangers. However, I doubt that modeling all the individual and poorly understood components of the sink will lead to a very reliable extrapolation either - when you add together lots of uncertain things, the result is usually a great deal of uncertainty.

Anyway, if you buy that, we can put together the extrapolated carbon emissions, partially compensated by the growing sink, and project CO_2 out to mid-century:



Annual average concentration of CO_2 in the atmosphere since 1959 as measured by Keeling et al in Mauna Loa, Hawaii, together with model projections. Click to enlarge. Source: Keeling via ORNL.

My preferred linear baseline case is the plum line, and you can contrast that to the brown exponential emissions growth and the blue constant emissions at the 2004 level. Obviously the result contains the uncertainties that we just reviewed - will carbon emissions really grow approximately linearly, and is the rule-of-thumb for the sink adequate. However, the thing is visually plausible, and will serve as our baseline for further consideration in future posts.

What I would draw attention to right now is this. We are now about 100ppm over the pre-industrial value. We will hit 200ppm above the pre-industrial value in the late 2040s in in the linear model. We could view this value as some kind of approximate indicator of the driving force behind "weather problems" - mountain glaciers all melting, increased storm activity, record heatwaves, etc. So during the expected lifetime of anyone here under about 35-40, that driving force is going to double. Whether the system is likely to respond linearly to that is another day's subject.

Next I will talk about how much we should worry about these levels of CO_2. After that we'll have a look at the Kyoto protocol and its likely impact, and then we'll begin looking at how much of the 60 Gt/year of net primary productivity for carbon in biomass makes it into the economy, and where it goes. I have some interesting graphs of the total weight of matter the world economy processes each year as context for that.