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The lag between temperature and CO_2. (Gore's got it right.)

Filed under:

- Arctic and Antarctic
- Climate Science
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— eric @ 27 April 2007 - ( ) ( )

When I give talks about climate change, the question that comes up most frequently is this: "Doesn't the relationship between CO_2 and temperature in the ice core record show that temperature drives CO_2, not the other way round?"

On the face of it, it sounds like a reasonable question. It is no surprise that it comes up because it is one of the most popular claims made by the global warming deniers. It got a particularly high profile airing a couple of weeks ago, when congressman Joe Barton brought it up to try to discredit Al Gore's congressional testimony. Barton said:

> In your movie, you display a timeline of temperature and compared to CO_2 levels over a 600,000-year period as reconstructed from ice core samples. You indicate that this is conclusive proof of the link of increased CO_2 emissions and global warming. A closer examination of these facts reveals something entirely different. I have an article from *Science* magazine which I will put into the record at the appropriate time that explains that historically, a rise in CO_2 concentrations did not precede a rise in temperatures, but actually lagged temperature by 200 to 1,000 years. CO_2levels went up after the temperature rose. The temperature appears to drive CO_2, not vice versa. On this point, Mr. Vice President, you're not just off a little. You're totally wrong.

Of course, those who've been paying attention will recognize that Gore is not wrong at all. This subject has been very well addressed in numerous places. Indeed, guest contributor Jeff Severinghaus addressed this in one of our very first RealClimate posts, way back in 2004. Still, the question does keep coming up, and Jeff recently received a letter asking about this. His exchange with the letter writer is reproduced in full at the end of this post. Below is my own take on the subject.

First of all, saying "historically" is misleading, because Barton is actually talking about CO_2changes on very long (glacial-interglacial) timescales. On historical timescales, CO_2 has definitely led, not lagged, temperature. But in any case, it doesn't really matter for the problem at hand (global warming). We know why CO_2 is increasing now, and the direct radiative effects of CO_2 on climate have been known for more than 100 years. In the absence of human intervention CO_2 does rise and fall over time, due to exchanges of carbon among the biosphere, atmosphere, and ocean and, on the very longest timescales, the lithosphere (i.e. rocks, oil reservoirs, coal, carbonate rocks). The rates of those exchanges are now being completely overwhelmed by the rate at which we are extracting carbon from the latter set of reservoirs and converting it to atmospheric CO_2. No discovery made with ice cores is going to change those basic facts.

Second, the idea that there might be a lag of CO_2 concentrations behind temperature change (during glacial-interglacial climate changes) is hardly new to the climate science community. Indeed, Claude Lorius, Jim Hansen and others essentially predicted this finding fully 17 years ago, in a landmark paper that addressed the cause of temperature change observed in Antarctic ice core records, well before the data showed that CO_2 might lag temperature. In that paper (Lorius et al., 1990), they say that:

> changes in the CO_2 and CH_4 content have played a significant part in the glacial-interglacial climate changes by amplifying, together with the growth and decay of the Northern Hemisphere ice sheets, the relatively weak orbital forcing

What is being talked about here is influence of the seasonal radiative forcing change from the earth's wobble around the sun (the well established Milankovitch theory of ice ages), combined with the positive feedback of ice sheet albedo (less ice = less reflection of sunlight = warmer temperatures) and greenhouse gas concentrations (higher temperatures lead to more CO_2 leads to warmer temperatures). Thus, both CO2 and ice volume should lag temperature somewhat, depending on the characteristic response times of these different components of the climate system. Ice volume should lag temperature by about 10,000 years, due to the relatively long time period required to grow or shrink ice sheets. CO_2 might well be expected to lag temperature by about 1000 years, which is the timescale we expect from changes in ocean circulation and the

strength of the “carbon pump” (i.e. marine biological photosynthesis) that transfers carbon from the atmosphere to the deep ocean.

Several recent papers have indeed established that there is lag of CO_2 behind temperature. We don’t really know the magnitude of that lag as well as Barton implies we do, because it is very challenging to put CO_2 records from ice cores on the same timescale as temperature records from those same ice cores, due to the time delay in trapping the atmosphere as the snow is compressed into ice (the ice at any time will always be *older* than the gas bubbles it encloses, and the age difference is inherently uncertain). Still, the best published calculations do show values similar to those quoted by Barton (presumably, taken from this paper by Monnin et al. (2001), or this one by Caillon et al. (2003)). But the calculations can only be done well when the temperature change is large, notably at glacial terminations (the gradual change from cold glacial climate to warm interglacial climate). Importantly, it takes more than 5000 years for this change to occur, of which the lag is only a small fraction (indeed, one recently submitted paper I’m aware of suggests that the lag is even less than 200 years). So it is not as if the temperature increase has already ended when CO_2 starts to rise. Rather, they go very much hand in hand, with the temperature continuing to rise as the the CO_2 goes up. In other words, CO_2 acts as an amplifier, just as Lorius, Hansen and colleagues suggested.

Now, it there *is* a minor criticism one might level at Gore for his treatment of this subject in the film (as we previously pointed out in our review). As it turns out though, correcting this would actually further strengthen Gore’s case, rather than weakening it. Here’s why:

The record of temperature shown in the ice core is not a global record. It is a record of local Antarctic temperature change. The rest of the globe does indeed parallel the polar changes closely, but the global mean temperature changes are smaller. While we don’t know precisely why the CO_2 changes occur on long timescales, (the mechanisms are well understood; the details are not), we do know that explaining the magnitude of global temperature change requires including CO_2. This is a critical point. *We cannot explain the temperature observations without CO_2.* But CO_2 does not explain all of the change, and the relationship between temperature and CO_2 is therefore by no means linear. That is, a given amount of CO_2 increase as measured in the ice cores need not necessarily correspond with a certain amount of temperature increase. Gore shows the strong parallel relationship between the temperature and CO_2 data from the ice cores, and then illustrates where the CO_2 is now (384 ppm), leaving the viewer’s eye to extrapolate the temperature curve upwards in parallel with the rising CO_2. Gore doesn’t actually make the mistake of drawing the temperature curve, but the implication is obvious: temperatures are going to go up a lot. But as illustrated in the figure below, simply extrapolating this correlation forward in

time puts the Antarctic temperature in the near future somewhere upwards of 10 degrees Celsius warmer than present — rather at the extreme end of the vast majority of projections (as we have discussedhere).

Global average temperature is lower during glacial periods for two primary reasons:
1) there was only about 190 ppm CO_2 in the atmosphere, and other major greenhouse gases (CH4 and N2O) were also lower
2) the earth surface was more reflective, due to the presence of lots of ice and snow on land, and lots more sea ice than today (that is, the albedo was higher).
As very nicely discussed by Jim Hansen in his recent *Scientific American* article, the second of these two influences is the larger, accounting for about 2/3 of the total radiative forcing. CO_2 and other greenhouse gases account for the other 1/3. Again, this was all pretty well known in 1990, at the time of the Lorius et al. paper cited above.

What Gore should have done is extrapolated the temperature curve according this the appropriate scaling — with CO_2 accounting for about 1/3 of the total change — instead of letting the audience do it by eye. Had he done so, he would have drawn a line that went up only 1/3 of the distance implied by the simple correlation with CO_2 shown by the ice core record. This would have left the impression that equilibrium warming of Antarctica due to doubled CO_2 concentrations should be about 3 °C, in very good agreement with what is predicted by the state-of-the-art climate models. (It is to be noted that the same models predict a significant delay until equilibrium is reached, due to the large heat capacity of the Southern ocean. This is in very good agreement with the data, which show very modest warming over Antarctica in the last 100 years). Then, if you scale the Antarctic temperature change to a global temperature change, then the global climate sensitivity to a doubling of CO_2 becomes 2-3 degrees C, perfectly in line with the climate sensitivity given by IPCC (and known from Arrhenius's calculations more than 100 years ago).

In summary, the ice core data in no way contradict our understanding of the relationship between CO_2 and temperature, and there is nothing fundamentally wrong with what Gore says in the film. Indeed, Gore could have used the ice core data to make an additional and stronger point, which is that these data provide a nice independent test of climate sensitivity, which gives a result in excellent agreement with results from models.

A final point. In Barton's criticism of Gore he also points out that CO_2 has sometimes been much higher than it is at present. That is true. CO_2 may have reached levels of 1000 parts per million (ppm) — perhaps much higher — at times in the distant geological past (e.g. the Eocene, about 55 million years ago). What Barton doesn't bother to mention is that the earth was much *much* warmer

at such times. In any case, more relevant is that CO_2 has not gone above about 290 ppm any time in the last 650,000 years (at least), until the most recent increase, which is unequivocally due to human activities.

Below is the letter written to Jeff Severinghaus, and his response:

Dear Jeff,

I read your article “What does the lag of CO2 behind temperature in ice cores tell us about global warming?” You mention that CO2 does not initiate warmings, but may amplify warmings that are already underway. The obvious question comes up as to whether or not CO2 levels also lag periods when cooling begins after a warming cycle… even one of 5,000 years?

If CO2 levels on planet Earth also lag the cooling periods, then how can it be that CO2 levels are causally related to terrestrial heating periods at all? I am not sure what the ice core records are related the time response of CO2 to the cooling trends. If there is also a lag in CO2 levels behind a cooling period, then it appears that CO2 levels not only do not initiate warming periods but are also unrelated to the onset of cooling periods. It would appear that the actual CO2 levels are rather impotent as an amplifier either way… warming or cooling. We are talking about planet Earth after all and not Venus whose atmospheric pressure is many times larger than Earth’s.

If there is also a time lag upon the onset of cooling, then it appears that some other mechanism actually drives the temperature changes. So what is the time difference between CO2 levels during the onset of a cooling period at the end of a warming period and the time history of the temperature changes in the ice cores?

Dear John,

The coolings appear to be caused primarily and initially by increase in the Earth-Sun distance during northern hemisphere summer, due to changes in the Earth’s orbit. As the orbit is not round, but elliptical, sunshine is weaker during some parts of the year than others. This is the so-called Milankovitch hypothesis [this really should say "theory" -- eric], which you may have heard about. Just as in the warmings, CO2 lags the coolings by a thousand years or so, in some cases as much as three thousand years.

But do not make the mistake of assuming that these warmings and coolings must have a single cause. It is well known that multiple factors are involved, including the change in planetary albedo, change in nitrous oxide concentration, change in methane concentration, and change in CO2 concentration. I know it is intellectually satisfying to identify a single cause for some observed phenomenon, but that unfortunately is not the way Nature works much of the time.

Nor is there any requirement that a single cause operate throughout the entire 5000 – year long warming trends, and the 70,000 year cooling trends.

Thus it is not logical to argue that, because CO2 does not cause the first thousand years or so of warming, nor the first thousand years of cooling, it cannot have caused part of the many thousands of years of warming in between.

Think of heart disease – one might be tempted to argue that a given heart patient's condition was caused solely by the fact that he ate french fries for lunch every day for 30 years. But in fact his 10-year period of no exercise because of a desk job, in the middle of this interval, may have been a decisive influence. Just because a sedentary lifestyle did not cause the beginning of the plaque buildup, nor the end of the buildup, would you rule out a contributing causal role for sedentary lifestyle?

There is a rich literature on this topic. If you are truly interested, I urge you to read up.

The contribution of CO2 to the glacial-interglacial coolings and warmings amounts to about one-third of the full amplitude, about one-half if you include methane and nitrous oxide.

So one should not claim that greenhouse gases are the major cause of the ice ages. No credible scientist has argued that position (even though Al Gore implied as much in his movie). The fundamental driver has long been thought, and continues to be thought, to be the distribution of sunshine over the Earth's surface as it is modified by orbital variations. This hypothesis was proposed by James Croll in the 19th century, mathematically refined by Milankovitch in the 1940s, and continues to pass numerous critical tests even today.

The greenhouse gases are best regarded as a biogeochemical feedback, initiated by the orbital variations, but then feeding back to amplify the warming once it is already underway. By the way, the lag of CO2 of about 1000 years corresponds rather closely to the expected time it takes to flush excess respiration-derived CO2 out of the deep ocean via natural ocean currents. So the lag is quite close to what would be expected, if CO2 were acting as a feedback.

The response time of methane and nitrous oxide to climate variations is measured in decades. So these feedbacks operate much faster.

The quantitative contribution of CO2 to the ice age cooling and warming is fully consistent with current understanding of CO2's warming properties, as manifested in the IPCC's projections of future warming of 3±1.5 C for a doubling of CO2 concentration. So there is no inconsistency between Milankovitch and current global warming.

Hope this is illuminating.

Jeff