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ARTICLES

The Case for Carbon Dioxide

John Staddon · Peter Morcombe

Despite hints of a "pause" in recent decades, there is general agreement that the earth's climate is warming, especially in the northern hemisphere. A tiny town in Greenland, Ilulissat, is seeing icebergs crumbling off the local glacier more rapidly each year. The effects are not all bad, though. Tourism is booming in Ilulissat, access to metal-ore sites is easier and the fishing harbor can be used for most of the year.

The consequences elsewhere are less agreeable, however. A warming climate causes sea level to rise, by thermal expansion and by the melting of land ice in Greenland and elsewhere. Low-lying settlements are vulnerable to inundation. On the other hand, the Antarctic, containing as it does some 90 percent of the planet's ice, is the biggest threat and shows little sign of warming, except at its edges. It may even be that the total ice cover of Antarctica is actually growing slowly. But if the sea expands, by thermal expansion and by the addition of melting land-ice, many coastal communities will be under stress. (Just to confuse things, the latest reports seem to show the Ilulissat glacier growing again.)

Never mind the uncertainties. The consensus is that the planet is warming and will continue to do so, that it will cause the sea level to rise, and will also increase the frequency of severe weather events like hurricanes, tornadoes and, wildfires.

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Peter Morcombe is an electrical engineer who has worked with physics Nobelist Charles Kao on long-haul optical fiber and physicist John Madey on the free-electron laser. He has long been skeptical of the AGW hypothesis and works on physical climate models.

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Some critics, from a troubled Swedish teenager to the president of Harvard University, say we are facing a crisis of biblical proportions. “Listen to the scientists . . . unite behind the science . . . take real action,” young Ms. Thunberg told U.S. lawmakers, while the head of our leading academic institution admonishes us: “[W]e must face up to the stark reality of climate change. The scientific consensus is by now clear . . . Climate change poses an immediate and concrete test of whether we . . . will fulfill a sacred obligation: to enable future generations to enjoy, as we are privileged to enjoy, the wonders of life on Earth.”[1]

We agree that science should decide. The problem is that the science is often equivocal. There are passionate advocates on both sides of the climate issue. There are websites (so-called “climate deniers”) skeptical of any human agency in climate change, if not of climate change itself. There is at least one website solely devoted to criticism of deniers as well as many presenting, or assuming, the case for human-caused change.

One thing should be clear: *there is no consensus.* There is no scientific unanimity about the causes of climate change or even about the magnitude of the change. A second thing that should be even more widely understood is that consensus is in fact irrelevant. Science is not a democracy; truth cannot be decided by vote. There are many examples from the history of science—from phlogiston theory to continental drift, not to mention confident contemporary prescriptions for our diets—where the “consensus” was in fact wrong.

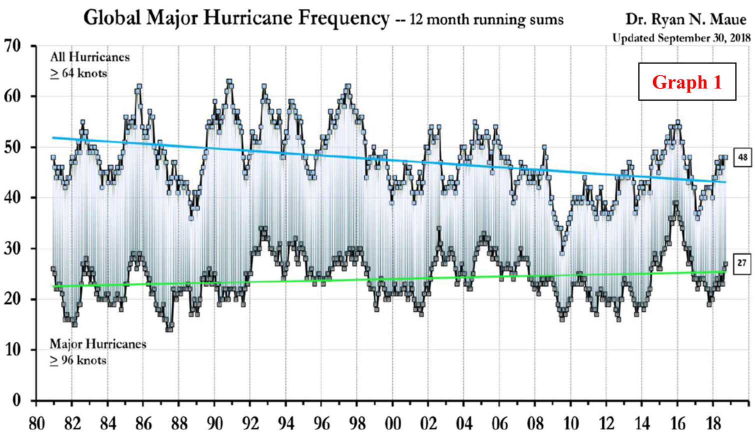
In this piece we try to present an objective, comprehensive, and readable summary of the science, bearing in mind the multiplicity of sources and the fact that passionate politics affects almost all of them. Our reading has brought us to conclusions that are far from apocalyptic. There are even reasons for optimism. Is “aggressive action” really required? We see nothing in the science that compels drastic measures. We may be wrong, but we have tried in as brief a space as possible to explain why we are skeptical of a fictional consensus. Let’s look first at some trends.

Hurricanes, Tornadoes, and Droughts

Perhaps because images and videos of dramatic events are now so widely publicized on the internet as well as TV, and perhaps because so many people are primed to see climate change as a cause of any climate disaster, there is an

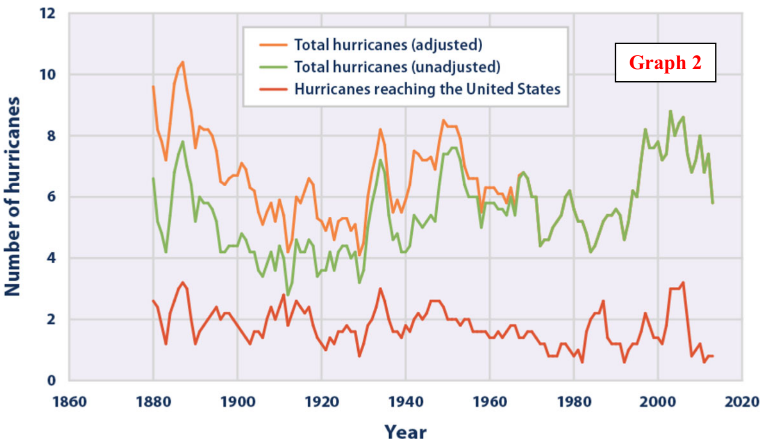
[1] Lawrence S. Bacow, President of Harvard University, Fall 2019.

overwhelming public impression that the frequency of natural disasters has greatly increased in recent decades. Do the statistics and the data actually support the popular impression? A Google search reveals a dozen or more graphs of hurricane frequency over the last fifty or a hundred years. Graph 1 is one of the more detailed: it shows data on hurricanes—all hurricanes—from 1980 to 2018. Hurricane intensity is derived by combining force and duration. Major hurricanes have increased a little, hurricanes as a whole have declined in frequency. There is no obvious trend.

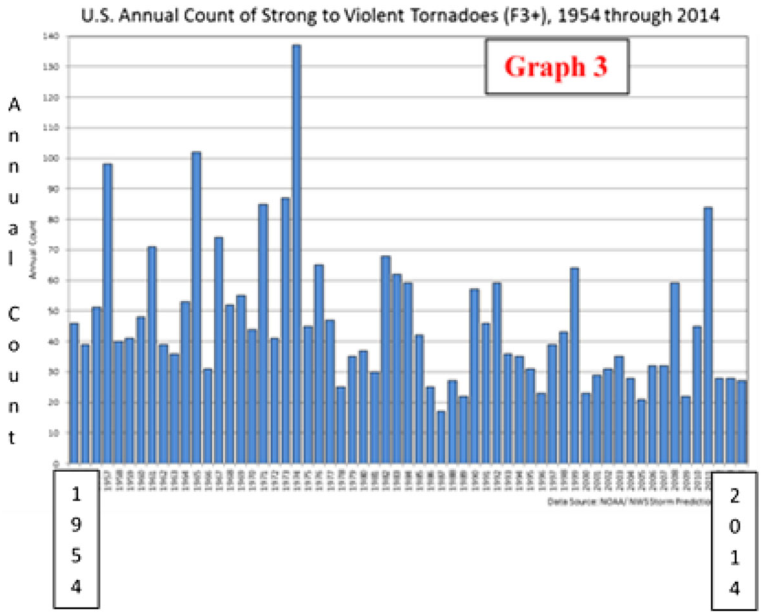


Graph 2, from the U.S. Environmental Protection Agency (EPA), goes a little further back, to 1860, covering hurricanes and other tropical storms in the Atlantic Ocean, Caribbean, and Gulf of Mexico. Only the number of hurricanes is counted since the early data allows nothing more precise. But again, there seems to be no trend. Our search shows many confirming, and few discrepant, graphs. Most data agree that there is no trend over the past 150 years or so. The problem is not the hurricanes, but growth of population and structures in risky areas: "While neither U.S. landfalling hurricane frequency nor intensity shows a significant trend since 1900, growth in coastal population and wealth have led to increasing hurricane-related damage along the U.S. coastline."[2] It seems to be the amount of damage, rather than the frequency of hurricanes, that has led to the public impression that hurricanes are becoming more frequent and more severe.

[2]Klotsbach, Bowen, Pielke, and Bell, "Continental U.S. hurricane landfall frequency and associated damage: observations and future risks," *American Meteorological Society* (July, 2018): 1359-1377.

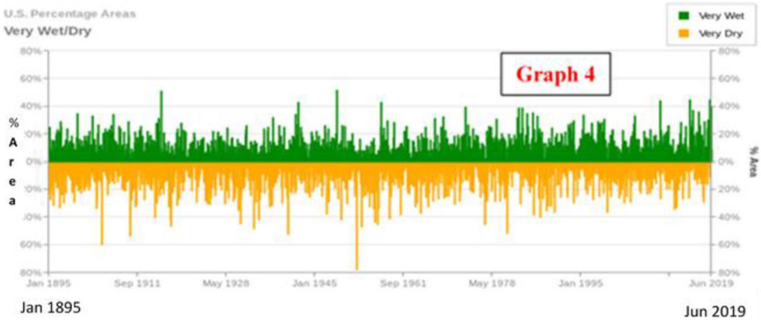


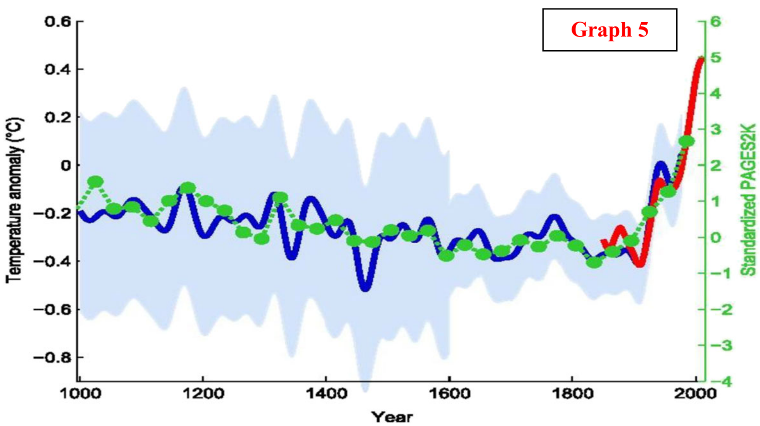
Graph 3 shows National Oceanic and Atmospheric Administration (NOAA) data on strong tornadoes in the U.S., from 1954 to 2014. Again, there is no (recent) trend. *The Wonderful Wizard of Oz* (1900) was inspired by tornadoes in Kansas in the nineteenth century; tornadoes are not a new phenomenon in America. Graph 4 is NOAA data showing wet and dry periods in the U.S. from 1895 to 2019, with no trend. Similar data are available for summer heatwaves, bitter winters, and droughts. In short, there is really no good evidence that warming climate is causing more extreme weather events.



Temperature

There is some evidence that northern hemisphere temperature has increased in the past several decades. Graph 5 shows the well-known "hockey stick" graph of Michael Mann et al., first published in 1999. The graph shows deviations ("anomalies") from a northern hemispheric mean temperature from AD 1000 through 1998. (The different lines and symbols are different averages and the red line is global temperature; the pale blue area is an estimate of uncertainty.) The older temperatures had to be estimated by a sophisticated statistical model using proxies, such as tree rings from a few specimens of a long-lived Rocky Mountain pine, varved (layered) sediments, ice cores, corals, and the like. Only the recent data (i.e. the red line) are direct measurements. (Even direct measurements are not without problems as indicators of global temperature: completeness of coverage—the location of the thermometers—"heat island" effects of cities, seasonal variation, and the like.)



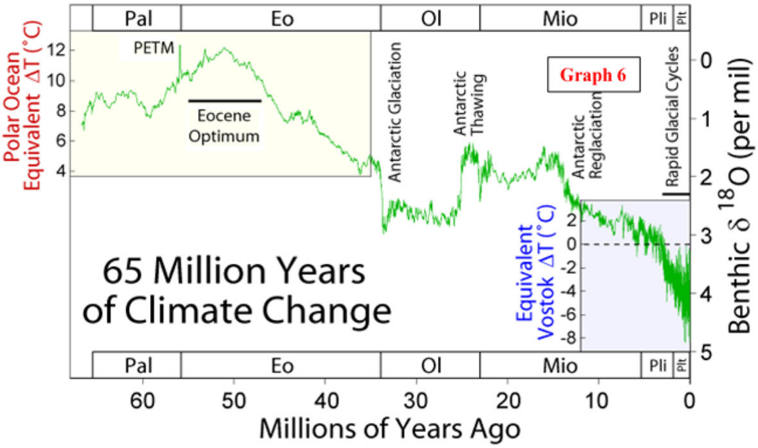


The hockey stick caught on because it shows a slow decline in hemispheric temperature from 1000 AD, followed by a dramatic increase coinciding with the rise of Western industry after 1850 or so. The inference that humanity is responsible for this sharp rise is hard to resist. The hockey stick graph has been widely criticized. After several disputes, including an ongoing law suit, a 2006 congressionally sponsored report concluded that "global mean surface temperature was higher during the last few decades of the twentieth century than during any comparable period during the preceding four centuries"; but there is still credible, reasoned dissent. There is also good historical evidence for a European medieval warm period (MWP) from about AD 950 to AD 1250, which was followed by a brief "little ice age." This bump does not show up in the hockey stick.

The temperature of at least the northern hemisphere *may* have increased substantially, if not smoothly, over two periods during the last one-thousand years: the MWP and the recent hockey stick upturn. The MWP was followed by a temperature decline, but majority opinion expects the current increase to continue. We get to the reasons for this belief in a moment.

How does the contemporary situation compare with earlier epochs? We need go back no further than the last 100 million years or so, the period during which mammals evolved. Presumably, humanity could have existed at any time during that period, although the current version now says that mammals evolved during the last 300 million years or so.

Graph 6 shows global temperature from 65 million years ago to the present. Temperature is estimated by the proportion of the oxygen-18 isotope, a proxy from the hardened fossil shells of benthic foraminifera taken from ocean sediments. Conversion to temperatures is tricky. The usual estimate is that 1 part per thousand of ^{18}O corresponds to 1.5 -2.0 °C. Never mind the precise scale, the graph clearly shows that temperatures in recent times, the last several thousand years, were in fact much lower than they were in earlier periods.



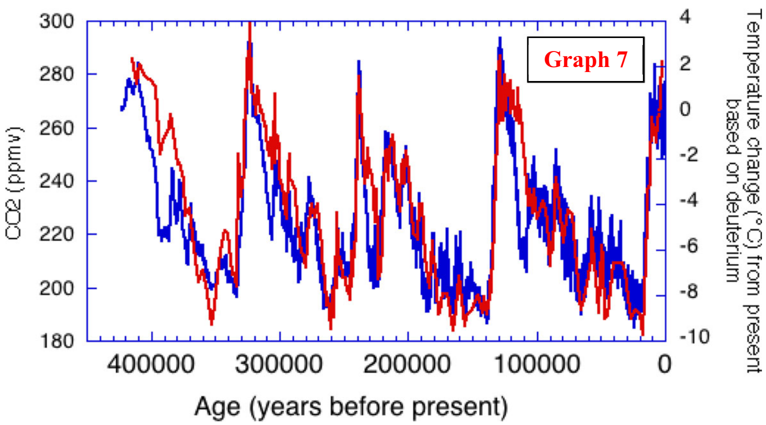
Perhaps we should only be concerned with the period when modern man roamed the earth, just the past 300,000 years or so. Graph 7 shows the covariation of carbon dioxide (the red line) and temperature, a topic we will return to in a moment. For now, look at the blue line, which shows temperature change (measured as it must be by a proxy method: Antarctic ice cores) relative to the present. Temperature has varied in quite large cycles from 400,000 years ago until now. Present temperature is close to a peak. Nevertheless, it is clear that the earth's temperature has been as high or higher than the present temperature during three or four earlier periods, and that previous peaks occurred in the presence of *Homo sapiens*, but without the aid of man-made CO2. So, unless the recent temperature rise is not part of the historical pattern, but due to a unique new factor which is forcing the rise, humans and higher temperatures can coexist. No apocalypse is in prospect.

Carbon Dioxide: the AGW Hypothesis

Pause or no pause, the temperature of the globe, especially the northern hemisphere, has generally risen for the past 150 years or so. Is human activity responsible? The claim that human-produced carbon dioxide, CO2, is the cause of this warming is the *anthropogenic global warming* (AGW) hypothesis.

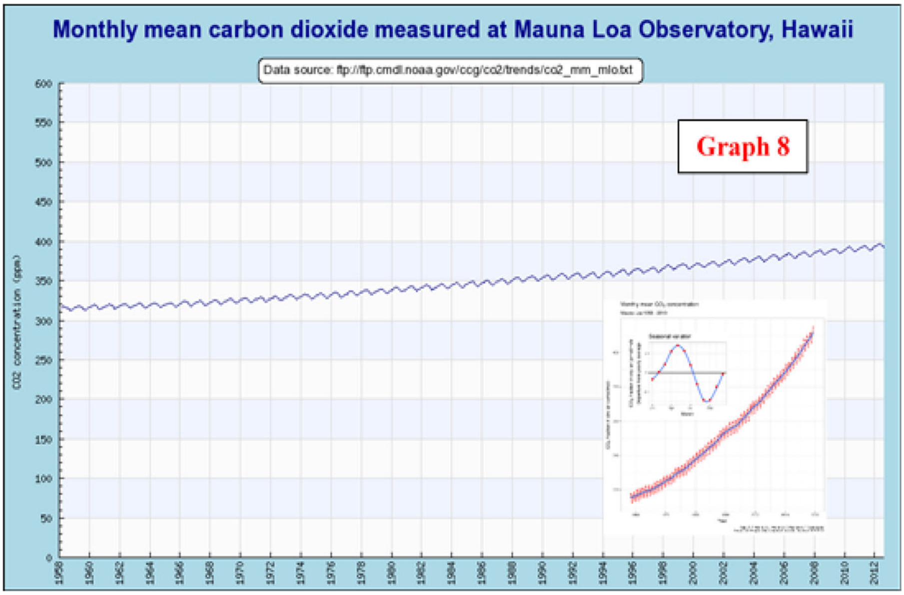
AGW is one possibility. The other is that global (or at least northern-hemisphere) temperature is just following the natural temperature cycle, like the previous peaks in Graph 7. Human activity is irrelevant. The investor's motto: "Past performance is no guarantee of future results" is appropriate. The cause is not human, and no mitigation is possible—and there is no reason for undue anxiety.

Carbon Dioxide: the AGW Hypothesis



But AGW is the idea that has captured activists' imagination. The main reason is one of the few bits of hard data available to climate science: the *Keeling curve*. Graph 8 shows atmospheric CO2 levels measured at the Mauna Loa Observatory in Hawaii from 1958 to the present. The jiggles are seasonal variation: less CO2 after northern summers, because most plant life on the planet is in the northern hemisphere and plants consume CO2 (inset). The inset shows the same Keeling curve as usually displayed, with a truncated y-axis, which makes the slope look steeper.

The curve shows a slow upward trend: atmospheric CO2 levels are increasing. The conclusion that the recent (since 1900 or so) rise in hemispheric temperature is caused by the parallel rise in atmospheric CO2 (Graph 7) is easy to draw. Many people, and not a few governments, are convinced that humanity is responsible for the Keeling increase, that CO2 is a major driver of global temperature, and that humanity is therefore the chief cause of global warming. Most climate scientists[3] and many placard-waving demonstrators across the world therefore urge action. We must take drastic steps to reduce CO2 emission caused by burning fossil fuels.



But is it true that recent temperature rise is caused by the rise in CO2? CO2 is less than 400 parts per million, 0.04 percent, of the atmosphere; it is, so far at least, slowly increasing (Graph 8). Only about 4 percent of that 0.04 percent is

[3] Although probably fewer than the oft-quoted "97 percent."

caused by human activity. CO_2 is much less effective as a greenhouse gas than water vapor (average 0-4 percent of the atmosphere), not to mention clouds. Is it even true that the (questionable) hockey stick temperature increase is due to some human activity? Quite possibly not, since there are in fact compelling data showing almost indistinguishable pre- and post-industrial temperature increases.

But CO_2 is the focus: does the tiny human addition to the small amount of CO_2 naturally in the atmosphere really have a significant effect on the temperature of the planet, and how do we know? And is it true that predicted increases in the earth's temperature threatens human life? The earth would be uninhabitable but for an atmosphere that contains greenhouse gases, like water vapor and CO_2, which limit the amount of the sun's heat re-radiated back into space: "Without greenhouse gases, the average temperature of Earth's surface would be about -18 °C below zero, rather than the present average of 15 °C (59 °F). (In fact, more recent models suggest a moon—i.e., atmosphere-free—average closer to -75 °C.) Have we now got too much of a good thing?

Models

There are two ways to find out. The most widely discussed is via climate models, which are described as follows on the NOAA site:

> Climate models are based on well-documented physical processes to simulate the transfer of energy and materials through the climate system. [They] . . . use mathematical equations to characterize how energy and matter interact in different parts of the ocean, atmosphere, [and] land. Building and running a climate model [involves] identifying and quantifying Earth system processes, representing them with mathematical equations, setting variables to represent initial conditions and subsequent changes in climate forcing, and repeatedly solving the equations using powerful supercomputers.

Climate modeling is obviously complicated; the outcome depends on the assumptions on which the model is based, and the relative weights given to different factors. The effects of clouds, for example, are complex and rarely included in these models. All this is quite well explained, with a mathematical example, in Wikipedia.

Climate models and weather models are similar in that both are tuned to match existing data. This is called retrodiction or hindcasting; an older term is simply "fitting." The parameters of the model are adjusted until its output matches an existing data set as closely as possible. The tuned model is then used to predict.

Any theory that deserves to be called scientific must make testable predictions. Climate models are often compared to weather models, but the differences are instructive. Weather models are tested every day; they are pretty accurate in predicting the weather tomorrow and perhaps a day or two after. Hurricane-track models are an intermediate case: they can only be tested when hurricanes occur, a few times year. There are several hurricane models and, as we might expect, they don't agree and are often very wrong. Climate models are the worst possible case: they make predictions over tens or even hundreds of years. From a practical point of view, *they are untestable*. How accurate can we expect them to be?

The difficulty of climate modeling is underlined by the number of different models that are available. There is only one model of planetary attraction, Newton's, and even it doesn't always yield an easy answer. Climate models yield many answers and we don't know which, or whether any, is correct.

We can illustrate the problems with retrodiction with a famous and for-a-while-successful model in a different area: the Black–Scholes financial model (BSM). The dataset to which the model was fitted was past stock prices. The model gives a precise value for an option and did very well for a while, lifting the investment firm Long Term Capital Management (LTCM) high into the financial firmament in just three years. BSM is a good illustration of the retrodictive technique because all the parameters of the model but one can be directly measured. The one parameter that must be estimated from past data is *volatility*, the moment-to-moment variability in a stock price.

BSM worked well for LTCM for three years, but then market volatility increased, for reasons outside the scope of the model. The model's predictions were wrong and the firm LTCM collapsed, almost bringing the financial system down with it. Past performance really is no guarantee of future results. In other words, the parameters of a model that are estimated from past data may or may not be stable. The parameters in Einstein's equation $E = mc^2$, m and c, mass and the velocity of light, are directly measurable. But what are called *fitted parameters* are just estimates from the past. They may change in the future, in which case model predictions based on them will be wrong.

Climate models are much more complicated than the BSM. The most ambitious ones divide the atmosphere into millions of boxes (*voxels*); each voxel is set to certain initial conditions of temperature, pressure, wind, and atmospheric composition. These values are fed into a set of equations, making up millions of lines of computer code in the largest models. The equations change the values of the relevant dependent variables, such as temperature, pressure, and CO_2 concentration, from time-step to time-step, according to the processes they embody. The equations include well-established physical laws, like the Navier-Stokes equations, which describe the movement of viscous fluids, and the Arrhenius model for CO_2 temperature effects. Arrhenius's 1906 estimate, based on laboratory studies and the equations of physical chemistry, was that doubling the amount of atmospheric CO_2 should increase atmospheric temperature by 4^{o} C, which is close to what AGW advocates now believe.

Arrhenius's estimate was based on a closed system in a laboratory. Many other variables are at play in the real atmosphere, of course. But no matter how elaborate the model, no matter how much past data it incorporates, the same restriction applies to all models with fitted parameters: the future may not be like the past.

Correlations

There is a second way to assess the temperature effects of CO_2: to look at the historical record and see if temperature and CO_2 concentration covary. They do at certain time scales, but not at others. Graph 7 shows close covariation over the past 400,000 years. But, as we are frequently reminded and almost as frequently forget, correlation is not causation. The covariation could mean that CO_2 causes warming, or that oceans, warming for some other reason, release more CO_2. The latter is a simple fact that is easily demonstrated and well understood: warm water can retain less dissolved gas than cool water. We also know that CO_2, tiny as its concentration is in the atmosphere, can reduce heat re-radiation into space—but by exactly how much is uncertain. Does the correlation in Graph 7 reflect heating aided by CO_2 increase? Or does the CO_2 just add a little bit to heating from another source?

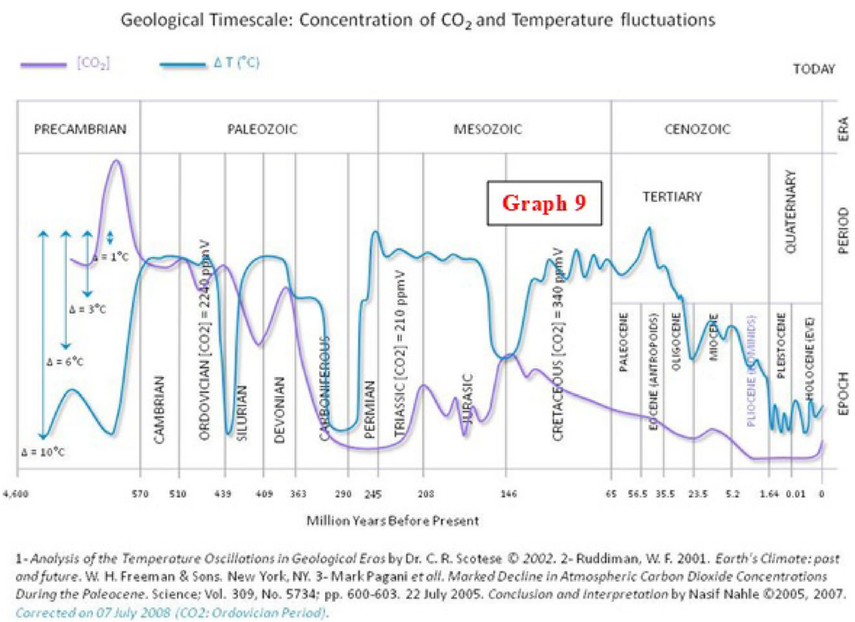
In fact, both effects seem to be operating. Global heating, caused by such things as changes in the earth's orbit and in solar output, causes a rise in global CO_2, as it is "outgassed" from warming oceans. The evidence for this is an acknowledged 800-year lag[4] going back some 800,000 years, the temperature rise *precedes* the subsequent rise in CO_2. Ocean heating increases CO_2. On the other hand, CO_2 does have some greenhouse effect and can therefore amplify an initially small temperature change. CO_2 increases may cause some heating, but just how much?

Graph 9, which is from a site critical of the AGW hypothesis, gives a hint. The graph shows estimates of CO_2 concentration and temperature from the most remote

[4]See the graph at Skeptical Science website, https://skepticalscience.com/co2-lags-temperature.htm

past to the present. Bear in mind that the older the estimate, the less reliable it is likely to be. If CO2 acts as a multiplier that can amplify small temperature changes into large ones, then we should see covariation between CO2 and temperature, as in Graph 7. Graph 9 covers much larger time and temperature scales and smooths over the relatively short-term changes in Graph 7. Graph 9 shows no, or even a negative, correlation between CO2 level and temperature.

We are not sure how much weight to put on these data. We can say that they provide no basis for anything more than a weak to non-existent positive feedback effect between CO2 and temperature. Can this feedback induce substantial warming by itself in the absence of exogenous forcing? Many, perhaps most, climate scientists believe it can. The data are not conclusive. The evidence that human-produced CO2 will *force* substantial increases in global temperature is in fact astonishingly weak.



How bad can it be?

The final issue is the effects of global warming. We have already seen that the earth has been warmer than it is now, even during the lifetime of the human species (Graph 7). People experience CO2 levels twenty or thirty times the atmospheric norm in crowded rooms every day. CO2, even well in excess of the current level, is not poisonous to humans. It is quite a stretch for the EPA to label it a pollutant.

Mankind can survive higher temperatures. Ilulissat is perfectly happy to see the glaciers melting and the sea warming. Siberia and Alaska probably feel much the same. On the other hand, low-lying settlements near the sea may be at risk. But of course, the people living in the Netherlands continue to adapt to sea levels that have risen for centuries. And London in 1982 erected the Thames barrier to protect the city from increasingly high tides; Venice will, in the fullness of time, likely do the same. There are ways to cope with rising sea level. The effects of temperature changes will be felt slowly, allowing plenty of time to adapt. But the rapidity of climate change and its unmanageability without radical changes in human behavior is simply taken for granted.

We know that increased atmospheric CO2 usually aids plant growth. Even NASA, which accepts the AGW hypothesis, acknowledges this, albeit rather grudgingly, headlining[5] that "CO2 is making Earth greener—for now." According to NASA: "A quarter to half of Earth's vegetated lands has shown significant greening over the last thirty-five years largely due to rising levels of atmospheric carbon dioxide, according to a new study published in the journal *Nature Climate Change.*"

Will this benefit persist, or will it be limited by other factors, as some have suggested? Are there other benefits to warming? After all more people seem to die of harsh winters than hot summers. If half as much time were to be spent studying the potentially beneficial effects of CO2 as in brooding over an impending apocalypse, perhaps the Extinction Rebellion folk would cheer up a bit. There are at least as many reasons for optimism as the reverse. We can see no reason for the end-of-days alarmism that now consumes so many. Perhaps the collective passion is just groupthink, another example of the contemporary madness of crowds. It certainly does not follow from science.

[5]See discussion and graphics at NASA website, https://climate.nasa.gov/news/2436/co2-is-making-earth-greenerfor-now/