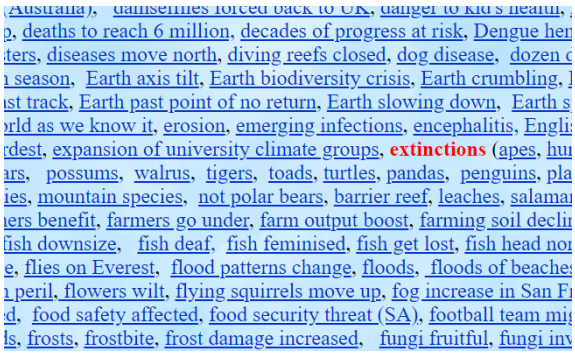
CO_2 and Climate: A Tutorial

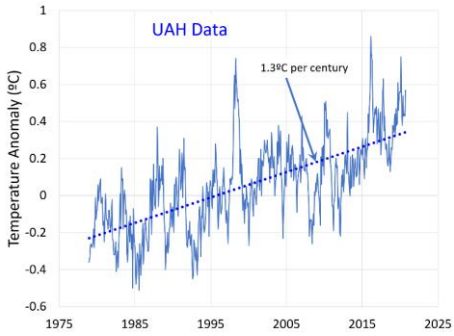
The number of bad things "scientists say" are due to "climate change" is certainly in the tens of thousands by now. Hardly a day goes by without the news media proclaiming another disaster caused by "climate change." By 2012, http://www.numberwatch.co.uk/warmlist.htm had the better part of a thousand links to claims of disaster linked to "climate change." The author of the website stopped adding links because the project was taking too much time.

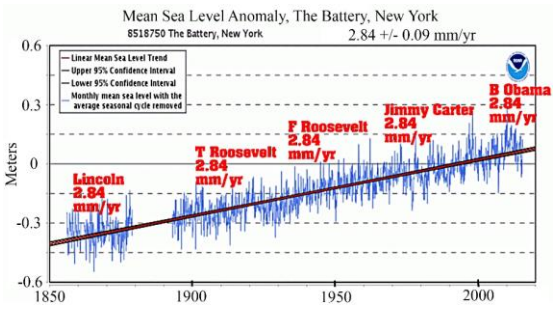


Recent examples: Kristen Rogers, "Bumblebees are going extinct because of the climate crisis, but there are easy ways to help," *CNN*. 02/06/2020; Peter Soroye, Tim Newbold, and Jeremy Kerr, "Climate change contributes to widespread declines among bumble bees across continents," *Science* **367**, 685–688, 7 Feb. 2020; A new 50-page report finds 30 "global-scale risks" at Marlowe Hood, "Scientists Warn Multiple Overlapping Crises Could Trigger 'Global Systemic Collapse,'" www.sciencealert.com, 5 Feb, 2020; Daniel Van Boom, "Iceland holds funeral for 700-year-old glacier killed by climate change," www.cnet.com, August 18, 2019;

More: Juliet Eilperin, "Climate change has stolen more than a billion tons of water from the West's most vital river," www.washingtonpost.com, Feb. 20, 2020; P. C. D. Milly* and K. A. Dunne, "Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation," *Science*, 20 Feb 2020; Justin Worland, "The Wuhan Coronavirus, Climate Change, and Future Epidemics," *Time*, February 6, 2020; Chris Ciaccia, "Climate change could destroy half of Earth's animal and plant species in the next 50 years, disturbing study says," www.foxnews.com, 2/13/2020; Cristian Román-Palacios and John J. Wien, "Recent responses to climate change reveal the drivers of species extinction and survival," Proc. Ntl. Acad. Sci., Feb 25, 2020; *Bloomberg News*: "Cacao plants are slated to disappear by as early as 2050 thanks to warmer temperatures and dryer [sic] weather conditions." "The First Undeniable Climate Change Deaths," Daniel Merino *EOS News*, 18 August 2020.

Satellite measurements—the only truly global system of temperature measurements—tell us that the average temperature of the earth is now rising at the rate of 1.3 ºC per century. It has been a half-century since screaming headlines quoting "experts" told us that the earth was heading into a new ice age because the temperature had gone down for a few decades. During the half-century since then, the temperature has risen by 0.65 ºC. At The Battery in lower Manhattan, which is slowly sinking (in the tectonic sense), sea level has risen at a steady rate of 2.84 mm/year, so in the 50-year span since the ice-age scare, sea level has risen there by 14.2 cm (5.6 inches), and that is an overestimate for global sea rise during the last 50 years. Did the climate change more rapidly this year than last year when such things didn't happen? Did this year's sea rise of the 2.84 mm (0.11 inch) at The Battery cause some disaster?





How, then, can "climate change" possibly be responsible for all of the bad things that happen? You can rest assured that self-respecting climate scientists cringe a little when politicians and the news media bloviate about climate disasters. However, their silence is deafening.

The purpose of this essay is to clarify the role of carbon dioxide in the climate. The discussion is numerical and graphical, but not mathematical. All the equations used in this paper are listed in the Appendix, and the reader is not asked to do any of the mathematics; however, we invite close scrutiny.

We simply follow the energy. We balance the checkbook, so to speak. If you, dear reader, have doubts, please consult your science friends to check the veracity. If there are any errors, I apologize, and sincerely ask you to point them out.

Seeking Expertise

Let us engage in a little creative history about climate knowledge. Suppose that you know about crop failures and crop abundances due to historical variations in climate. You also know about writings about weather on the walls of Chinese caves and hieroglyphics showing the Sahara looking like a savannah. You know a lot about past climate from studies of core samples of lake bottoms to see what seeds were prevalent. You understand the adiabatic lapse rate.

You know all the information gathered from ice cores in Antarctica and Greenland. You know about carbon dating (including the variability due to varying cosmic ray flux). You know about using oxygen isotope analysis to determine past temperatures. You know about tectonic plate movements, the rise of the Isthmus of Panama, and the effects of such things on ocean currents. You know the paleontology record forward and backward, and you know every detail about the Chicxulub event that killed off the dinosaurs.

You understand solar physics, the Stefan-Boltzmann radiation law, the Planck distribution, and the albedo of the earth. You understand the Milankovitch cycles. You can do potassium-argon dating in your sleep.

You've gotten the million-dollar Millennium Prize for solving the Navier-Stokes equation to enable you and everybody else to track the motion of fluids like oceans and the atmosphere. Let's suppose further that you know every computer language ever devised, and you have a way to link all of the world's supercomputers together.

In this little venture into creative history, with all that background knowledge, it suddenly occurs to you that the earth is warmer than it "should be," and that there might be something in the atmosphere causing the warmth. Since the only way for the earth to shed heat that comes from the sun is through radiation—and it has to be *infrared* radiation (IR)—you need to find somebody with expertise in the interaction between IR and the molecules in the atmosphere.

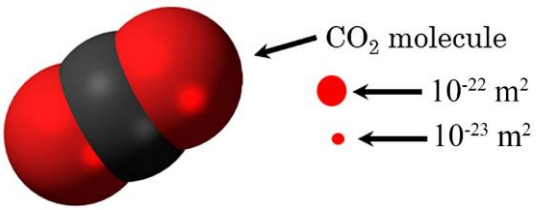
Now the question: Who has that kind of expertise? Al Gore? Bill McKibben? Michael Mann? Somebody at ABC, CBS, CNN, NBC, *The New York Times*, *The Washington Post*, *The Wall Street Journal* or NPR? Naomi Oreskes? Politicians? A Swedish teenager?

It is obviously wiser to consult scientists who have long careers in Atomic, Molecular and Optical (AMO) research. We'll do exactly that. Consider the next sections as a tutorial on the IR spectrum and CO_2.

A Basic Question Answered

An interesting question comes up: Is CO_2 a strong greenhouse gas? The answer: *It depends*.

Figure 1 shows the molecular cross-sectional area of CO_2 molecules to absorb infrared over the wavelength range of about 14 micro-meters (μm) to 16 μm. The spectrum extends quite a bit further in both directions, but the cross-sections are far too small to show up on the graph.



For the present concentration of CO_2, (400 parts per million) the "1" on the scale in Figure 1 results in a *mean free path* (average travel distance for the IR) of about one meter. For the lowest red line on the graph ("0.1"), IR travels only about 10 meters before being absorbed by a CO_2 molecule. If we had only one-tenth as much CO_2 as we presently have in the atmosphere (*i.e.*, 40 parts per million), any IR wavelength with a cross-section above 0.1 on the scale would travel at most 100 meters before being absorbed. (Mount Everest in nearly 9,000 meters high.) Even if we had a trifling one percent as much

CO_2 in the atmosphere as we have (namely a mere 4 parts per million), that IR would be absorbed in a kilometer.

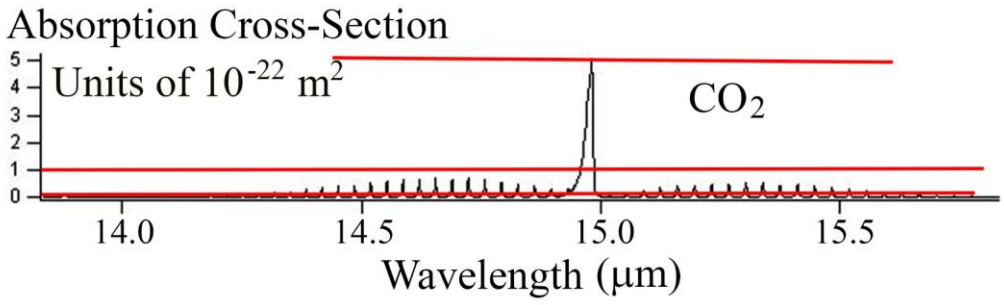
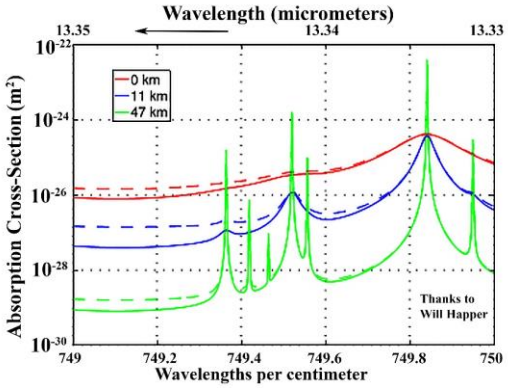


Figure 1: The cross-sectional area that IR passing through CO_2 must hit in order to be absorbed, versus IR wavelength.

The lesson here is that at *low concentrations*, CO_2 is a *very* effective IR absorber, hence a *very* effective greenhouse gas. By this, we mean that if a bit more CO_2 is added, the greenhouse effect increases substantially.

At higher CO_2 concentrations, adding more CO_2 does little to increase the greenhouse effect, for the simple reason that *most* (not all) of the IR that CO_2 *can* absorb is already absorbed. (The equivalent phenomenon in economics is called *diminishing returns*.) In fact, the current discussion among climate scientists is about how much greenhouse effect there would be if the *increase* in CO_2 concentration were 400 parts per million (*i.e.,* the concentration would be doubled from 400 to 800). The temperature rise due to a doubling of CO_2 concentration (with all that entails) is lovingly called the *sensitivity to doubling*. A second doubling (from 800 ppmv to 1,600 ppmv) would cause the same temperature rise.

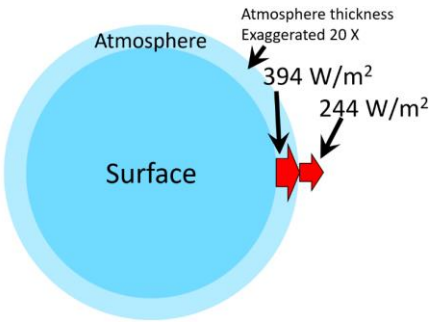


The additional greenhouse gas (GHG) effect would be caused only by absorption way out in the wings of the spectrum (toward 13 μm and 17 μm). The graph to the right shows that the cross-section is altitude-dependent because of the changes in pressure and temperature. The vertical scale of this logarithmic graph has its highest line at 10^{-22} m^2, the "1" of Figure 1; the lowest line (10^{-30} m^2) is lower by a factor of 100 million.

In other words, at very low concentrations, CO_2 is a strong GHG; at the present concentration, CO_2 is a weak GHG. This information has been around since long before Al Gore's *An Inconvenient Truth*, and long before the First Assessment Report (*FAR*) of the Intergovernmental Panel on Climate Change.

To modify a fashionable sentence: *Wavelength Matters.* Any "climate" discussion that ignores the details of the spectrum ignores the relevant science.

The Real Experts Speak



Sunlight reaches the earth's orbit with an intensity of about 1368 thermal watts per square meter. About 30% of that light is reflected, and 70% is absorbed. Seen from the sun, the earth is a disk whose area is πR^2. However, the earth is a sphere (we ignore the slight oblateness) whose area is four times as big, namely $4\pi R^2$. Therefore, the solar intensity, averaged over the sphere, is one-fourth of 70% of 1386 W/m², or 244 W/m². (Values from 235 to 244 W/m² have been published. None of what follows will be sensitive to that number. We choose 244 W/m² for this discussion.)

In the previous paragraph, we referred to the earth as a whole—that little bit of mass flying around the sun. However, in a climate discussion, we absolutely must distinguish between the earth as a whole and the surface—the continents, the oceans, and the lowest regions of the atmosphere. In equilibrium, the earth, as a whole, radiates exactly as much as it receives from the sun, namely 244 W/m², averaged over the sphere. However, the "warm" surface radiates 394 W/m², 150 W/m² more than the earth as a whole. When we refer to IR from the *earth*, we mean the earth as a whole.

> The earth, as a whole, radiates exactly as much as it receives from the sun, namely 244 W/m², averaged over the sphere. However, the surface radiates 394 W/m², 150 W/m² more than the earth as a whole.

At a recent meeting, Princeton Emeritus Professor of Physics Will Happer [1] presented an interesting graph (Figure 2) about the infrared spectrum emitted from the earth, and as absorbed by five greenhouse gases: H_2O, CO_2, N_2O, CH_4, and O_3. The spectrum is calculated from known properties of the molecules and the influences on the spectra caused by temperature (the Doppler effect) and pressure (varying with altitude).

Happer's graph [2], Figure 2, shows the effect of CO_2 at three different concentrations: zero, 400 ppmv (the present value), and 800 ppmv (double the present value).[1] The graph shows the amount of infrared (IR) versus the photon energy (in units of number of wavelengths per centimeter). The striking thing about the graph is that the change in IR absorption in going from 400 ppmv to 800 ppmv is quite trivial. Also notice that H_2O and N_2O absorb part of the IR in the CO_2 band, as seen with the CO_2 concentration set to 0 ppmv.

[1] To chemists, *ppm* means parts per million by mass, but in these calculations, it is parts per million by the number of molecules. Chemists use *ppmv*, parts per million by volume, which turns out to be exactly the same thing for gases.

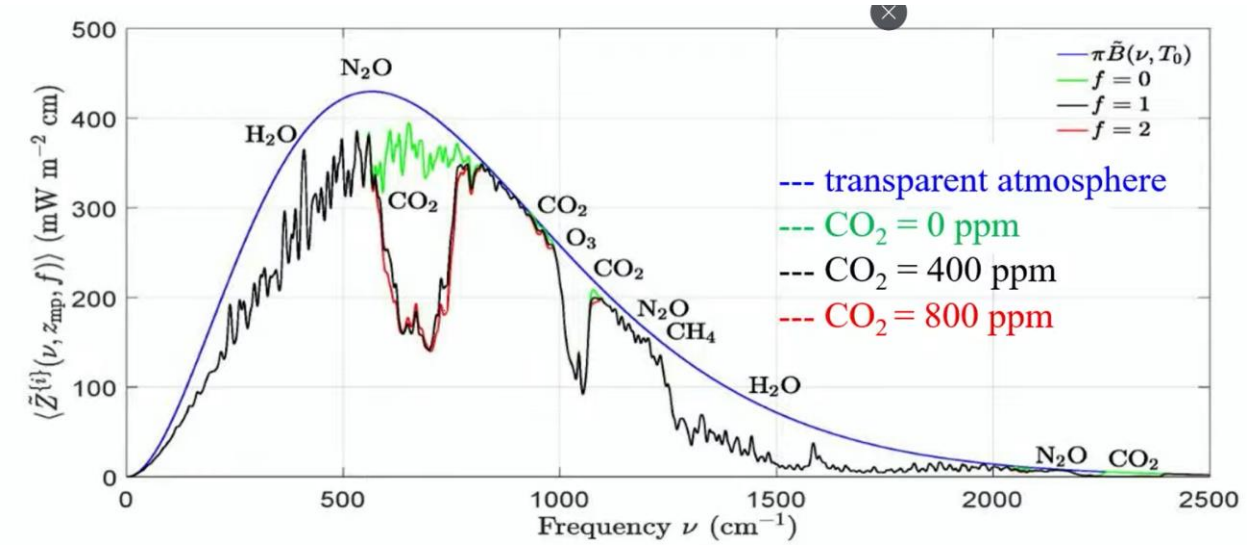


Figure 2: The IR spectrum of the earth with a transparent atmosphere, with fixed amounts of H_2O, N_2O, CH_4, and O_3, and with 0 ppmv, 400 ppmv, and 800 ppmv of CO_2. [1, graph from 2] The smooth upper line represents the IR emitted by the surface, the so-called *blackbody* curve.

I asked Professor Happer whether he'd be willing to do a slightly different calculation for me. What would the spectrum look like if the atmosphere had 200 ppmv, 100 ppmv, and 50 ppmv (one half, one-fourth, and one-eighth of present) CO_2 concentration? Very quickly, the answer came back from his colleague William van Wijngaarden, and is shown in Figure 3. The main effect of increasing concentration is a broadening of the absorption band. Even by 50 ppmv, CO_2 is already absorbing more than half of what it can absorb. The dashed curve in Figure 3 represents blackbody radiation from the surface, considered to be at an absolute temperature of 288.7 kelvins (271.15 ºC higher than the Celsius temperature of 15.55 ºC).

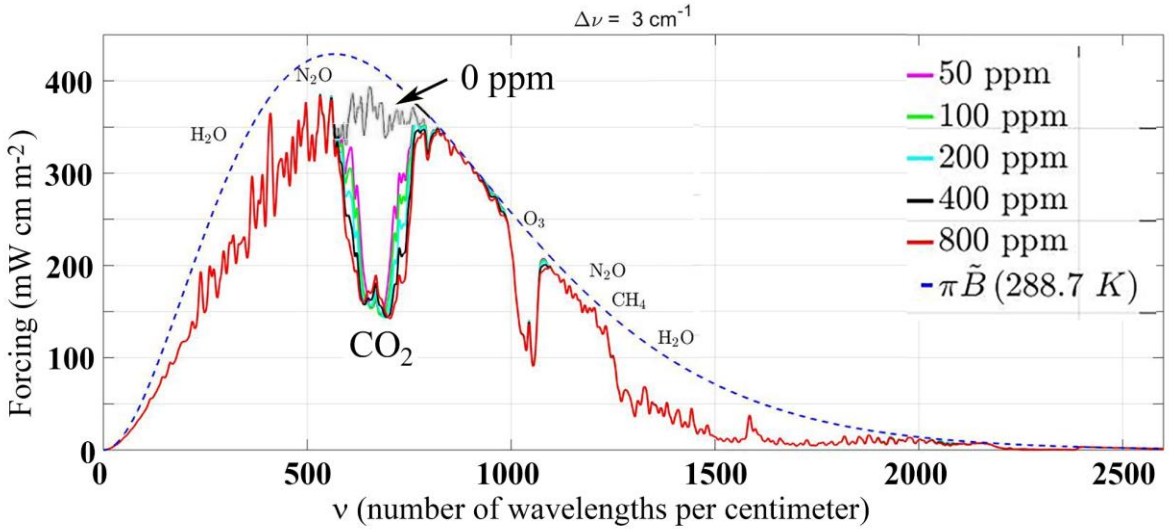


Figure 3: The effect on the IR spectrum of low concentrations of CO_2.

The whole story of the greenhouse effect of CO_2 (at its present concentration) revolves around that tiny change in IR absorption caused by a doubling from 400 to 800 ppmv seen in Figures 2 and 3. Any

warming caused by that increase heats the atmosphere and then the surface, which then responds by increasing the rate of radiation at all wavelengths.

[1] Will Happer, "Common Sense," https://www.youtube.com/playlist?list=PL3XZC6AmQVLGa8pHOQjmh664RGNeeQYEe talk #9.

[2] W. A. van Wijngaarden and W. Happer, "Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases," June 8, 2020, https://arxiv.org/pdf/2006.03098.pdf

Ruminations in the Press

An article in *Forbes* [3], advertised as the "simplest explanation ever" goes into considerable detail to explain the radiation from the sun (visible, IR, UV), the slight eccentricity of our orbit, the would-be temperature of the earth if there were no atmosphere, and so forth. Its final conclusion is that humans must be responsible for the warming, because the author can't think of anything else [3]:

> When we quantify the other effects, it's unlikely that anything else could be the cause. Not the Sun, not volcanoes, not any natural phenomenon that we know of.
>
> The Earth is warming, and humans are the cause.

The earth has warmed many hundreds of thousands of times in the last half-billion years, and certainly hundreds during that last 3 million years. "The earth is warming, and humans are the cause." Like always.

Siegel says (correctly) that the temperature of the earth (*if* it were an isothermal ball with exactly the same reflectivity but no atmosphere) would be 255 K, but that the surface temperature is actually 288 K, 33 K (= 33 ºC) higher. He adds [3]:

> According to NASA scientist Chris Colose:
>
> 50% of the 33 K greenhouse effect is due to water vapor, about 25% to clouds, 20% to CO_2, and the remaining 5% to the other non-condensable greenhouse gases such as ozone, methane, nitrous oxide, and so forth.

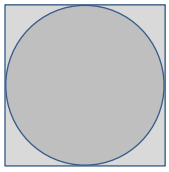
Let us accept his numbers. The effect of CO_2 is 20% of 33 ºC, or 6.6 ºC, and that contribution is almost all the IR-blocking[2] that CO_2 can provide. What would be the temperature rise if CO_2 absorbed a tiny bit more? We have noted that increases in CO_2 cause steadily less IR absorption: why should increases *now* cause *more* temperature rise?

At no time does Siegel mention anything about wavelengths, save to say that the sun emits ultraviolet, visible light, and infrared. His "simplest explanation" throws the baby out with the bathwater.

N.B.: Much, if not most, of the reflectivity of the earth is due to clouds, which would not exist if there were no atmosphere. The notion of a 255 K earth with no atmosphere but with exactly the same reflectivity (albedo) is clearly a fiction, though one commonly used to show the warming effect of the atmosphere. Measurements show that the earth has an overall albedo of about 30%, and it must therefore absorb 70% of the sunlight striking it. Equilibrium demands an exactly equal amount to be emitted by the earth. In any case, the earth must shed exactly as much IR as a blackbody at 255 K, even though the earth's radiation spectrum is not quite the same as that of a blackbody.

[3] Ethan Siegel, "The Simplest Explanation Of Global Warming Ever," *Forbes*, Jan 2, 2019.

More to the Story



It is often necessary to compare areas. For example, a child looking at a circle inscribed in a square will often estimate that the area of the circle is ¾ that of the square. (Indeed, it is $\pi / 4$, and that fact can be used to introduce them to $A = \pi R^2$.)

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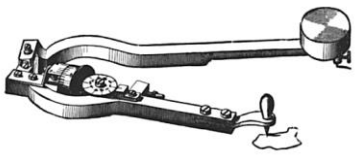
[2] In this essay, I refer to the blocking effect on the IR spectrum of CO_2 and other gases. The IPCC refers to the same thing somewhat aggressively as "forcing."

Often, especially with real data, there is no mathematical formula for some of the bounding lines, so other techniques have been invented. For example, a planimeter is a mechanical device designed over a century ago for the purpose of finding areas bounded by irregular lines by moving the probe around the periphery.



Another clever technique is what I call the chemists' method. It involves using scissors or a razor blade to cut around the important area, and then to weigh the paper with the accurate scales found in chemistry labs. In this exercise, we will use the cut-and-weigh technique. (I have a nice gem scale accurate to one milligram.)

Figure 4 shows three important parts of the IR spectrum excised from Figure 2 with a razor blade, and photographed against a dark background. Absent the numbers in Figure 4, one would estimate by eyeball that the area occupied by the bottom cutout is about 60% as large as that of the top. The top graph shows the blackbody spectrum emitted by the earth, considered to be at an average temperature of 288.7 K. By way of comparison, the value of 394 W/m^2 (watts per square meter averaged over the surface) here is in agreement with the 398 ± 5 W/m^2 shown in Figure 5 (there are various version in IPCC reports and elsewhere) at the bottom of the left-hand vertical stack.

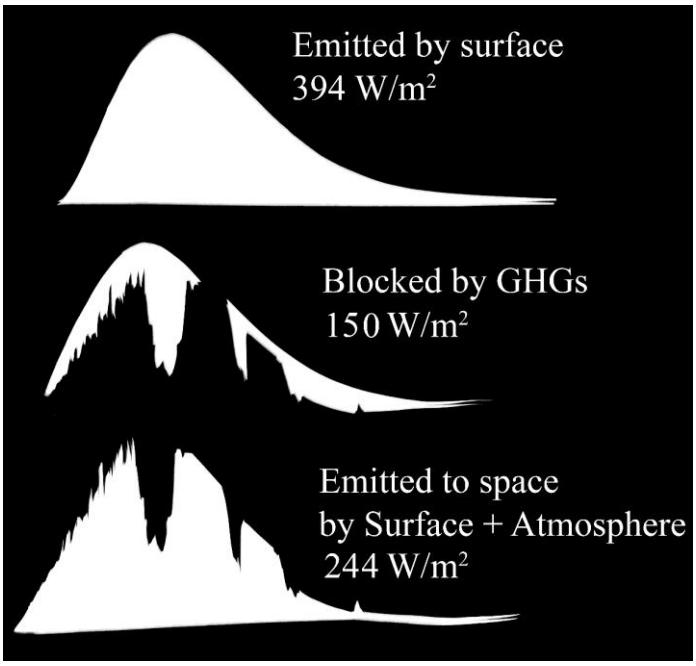


Figure 4. Razor cutouts of IR intensity vs. reciprocal wavelength (See Figs. 2 and 3 for numbers) Top: The IR spectrum emitted by the surface, treated as a blackbody at 288.7 K. Middle: Blocked IR. Bottom: IR emitted to space by the earth.

In equilibrium, the earth—as a whole—radiates away exactly as much power as it receives from the sun, namely, 244 W/m^2, is represented by the cutout at the bottom of Figure 4. That amount is to be compared to the difference between the incoming solar radiation (340.2 ± 0.1) and the reflected solar radiation (100.0 ± 2 W/m^2) of Figure 5.

What? No Zero?

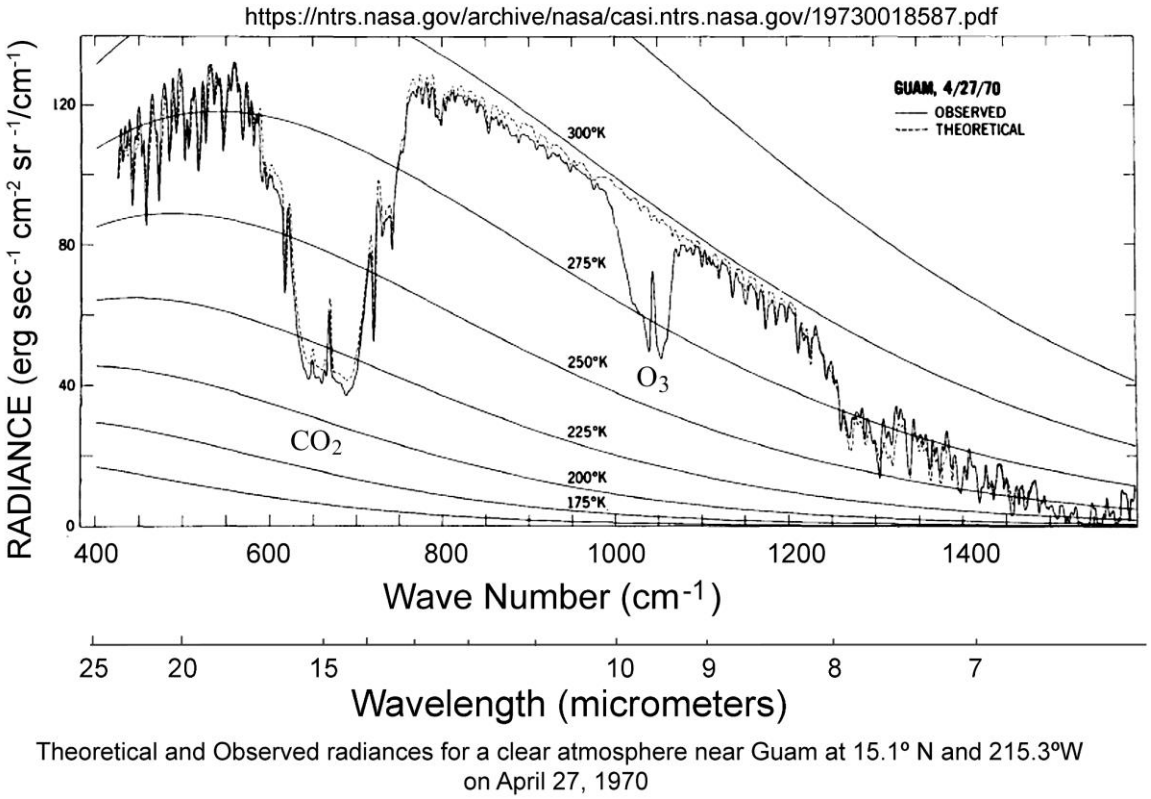
The observant reader will have noticed that the CO_2 part of the spectrum in Figures 2 and 3—and especially, in the bottom cutout in Figure 4—does not go all the way to zero, even though our previous discussion certainly implied that there was no chance for some of that radiation to make it to high altitude. Why could there be any IR whatsoever at those wavelengths?

When a carbon dioxide molecule absorbs an IR photon, it goes into one of numerous internal oscillation modes of vibration and rotation, depending on the energy of the IR photon. The molecule can shed that excitation energy by radiating IR, or it can shed it by colliding with other molecules in

the air, causing increased kinetic energy of the colliding molecule. That increases the (local) temperature.

The reverse process also happens. Collisions force the CO_2 molecule into excited states. In fact, the laws of statistical thermodynamics tell us that at atmospheric temperatures, there will always be a few percent of CO_2 molecules in those excited states. The excited modes are in equilibrium with the temperature of the surrounding air. At lower temperatures, there are fewer such molecules. The excited molecules can and do radiate IR.

At high-enough altitude, IR emitted by CO_2 can escape to outer space, because there is not much CO_2 above it. Measurements taken by satellites (above Guam, above the Sahara, and above the Atacama Desert, for example) show that the IR emission in the CO_2 band comes from a region where the temperature is about 215 K (–58 ºC; –73 ºF). Those super-frigid temperatures occur at an altitude about 10 times as high as Mt. Everest, where the atmospheric pressure is on the order of millionths of sea-level air pressure. That effect is shown as the bottom of the CO_2 notch as part of the 244 W/m² IR emitted to space, and similarly in Figure 4.



Theoretical and Observed radiances for a clear atmosphere near Guam at 15.1º N and 215.3ºW on April 27, 1970

Figure 4: Observed and theoretical radiances from a clear atmosphere near Guam April 27, 1970 [5].

Figure 4 provides us with some important information in this regard. It is obvious from Figure 1 that the wavelength least likely (if you're in the business of comparing negligible numbers) to radiate to outer space from the ground is that peak near 15 μm, but in Figure 4 it shows up to be a much stronger radiation that any other wavelength in the neighborhood. This is because that IR does not come from the ground; rather it is created at high altitude. A strong absorber is a strong radiator, on a line-by-line basis. In other words, the IR that goes into space in the CO_2 band is not due to a failure to block IR from the surface, but is actually produced at high altitude.

The other thing to be noticed in Figure 4 is that dotted theoretical line, which closely matches the CO_2 band but does not account for the ozone (O_3) band near 1100 cm^{-1}. Fifty years ago, they did an excellent job in calculating the CO_2 spectrum.

[5] The NIMBUS 4 Infrared Spectroscopy Experiment 2. Comparison of Observed and Theoretical Radiances from 425-1450 cm^{-1}

Off to Outer Space

The middle graph in Figure 4 shows the effect of greenhouse gases. It magnitude—150 W/m²— is the difference between the 394 W/m² emitted by the surface, and the 244 W/m² emitted to space. In this discussion, we refer to it as the blocked radiation.

Figure 5 also shows Sensible Heating (24 ± 7 W/m²) and Latent heating (88 ± 10 W/m²) as mechanisms that heat the atmosphere (while *cooling* the surface), as well as IR emissions from clouds (26.6 ± 5 W/m²) and from clear sky (187.9 ± 12.5 W/m²) which heat the surface and cool the atmosphere. The net result is that the surface is warmer that it would be if there were no atmosphere. All in all, it adds up to the 150 W/m² that is the difference between the heat radiated by the surface and the heat radiated to outer space.

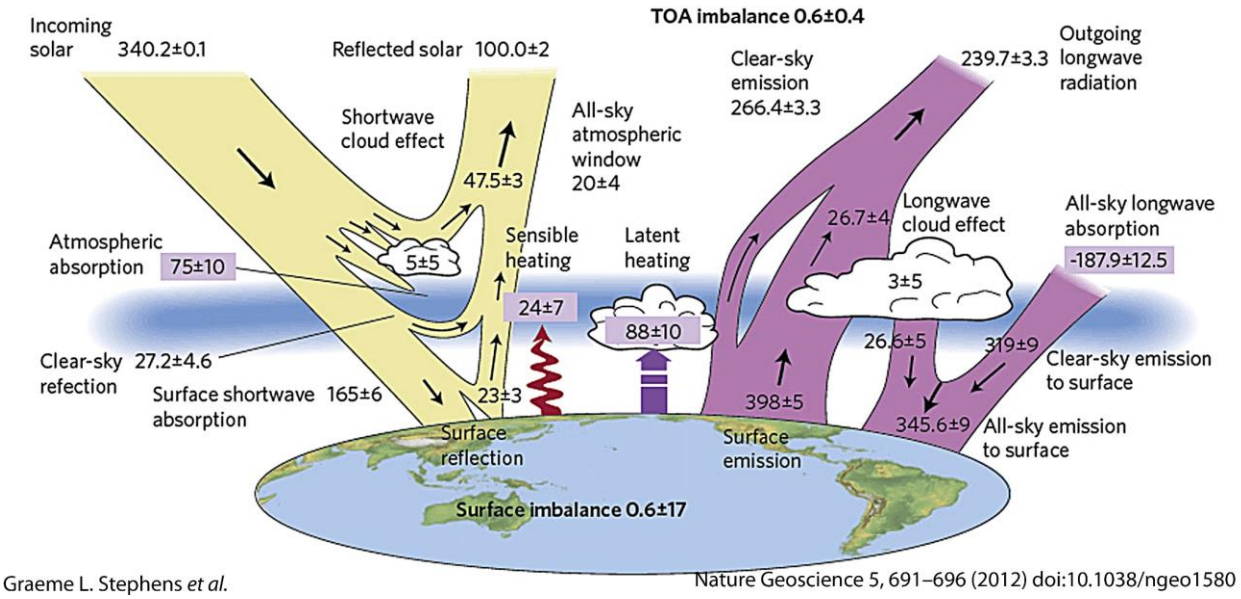
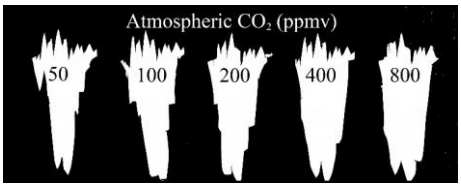


Figure 5: Heat balance of the earth from *Nature Geoscience*

Figure 5 also shows some of the numerous internal heat exchanges that are irrelevant to our present discussion; they have little or nothing to do with the net passage of IR to space. The reason for showing Figure 5 is to show that our numerical IR values agree with those of the IPCC and others.

The Role of CO_2

The greenhouse effect of CO_2 is calculable from the bounded areas in Figure 3. Cutouts of the CO_2 spectral areas corresponding to 50, 100, 200, 400,and 800 ppmv were excised from five prints of Figure 3, and photographed against a dark background, as shown in the picture to the right. (Owing to line thickness and overlap, great precision was not possible.) The computer program that generated Figure 3 could easily (and more accurately) be used to get the information, but it would provide no intuitive explanation about the underlying science.



An eyeball estimate shows that the three doublings (100 to 200, 200 to 400, and 400 to 800) each add about the same amount of area. Not shown in the picture is the 0-ppmv point, because would occupy no area at all.

When the weights of the CO_2 pieces are compared with the weight of the rectangle of the entire graph, the blocking in W/m² can be plotted against the CO_2 concentration, as shown in Figure 6.

Several things stand out in Figure 6. First, the IR blockage by 50 ppmv—only one-eighth of the present CO_2 concentration—is about 75% of the present amount of blockage by CO_2, just as we noted

above. Second, the present IR blockage is about 30 W/m², a mere 20% of the total (150 W/m²), in agreement with the 20% figure given by Siegel [3]. Third, the *increase* in blocking between 400 ppmv and its double at 800 ppmv is around 3 W/m², in approximate agreement with that (3.7 W/m²) used by the IPCC as far back as its Third Assessment Report in 2001, and 3.5 W/m² as used in present models. There is nothing controversial here. (In what follows, we will use 3.5 W/m², which is currently in vogue, although Happer's calculations show that the doubling should produce a "forcing" of under 3 W/m².)

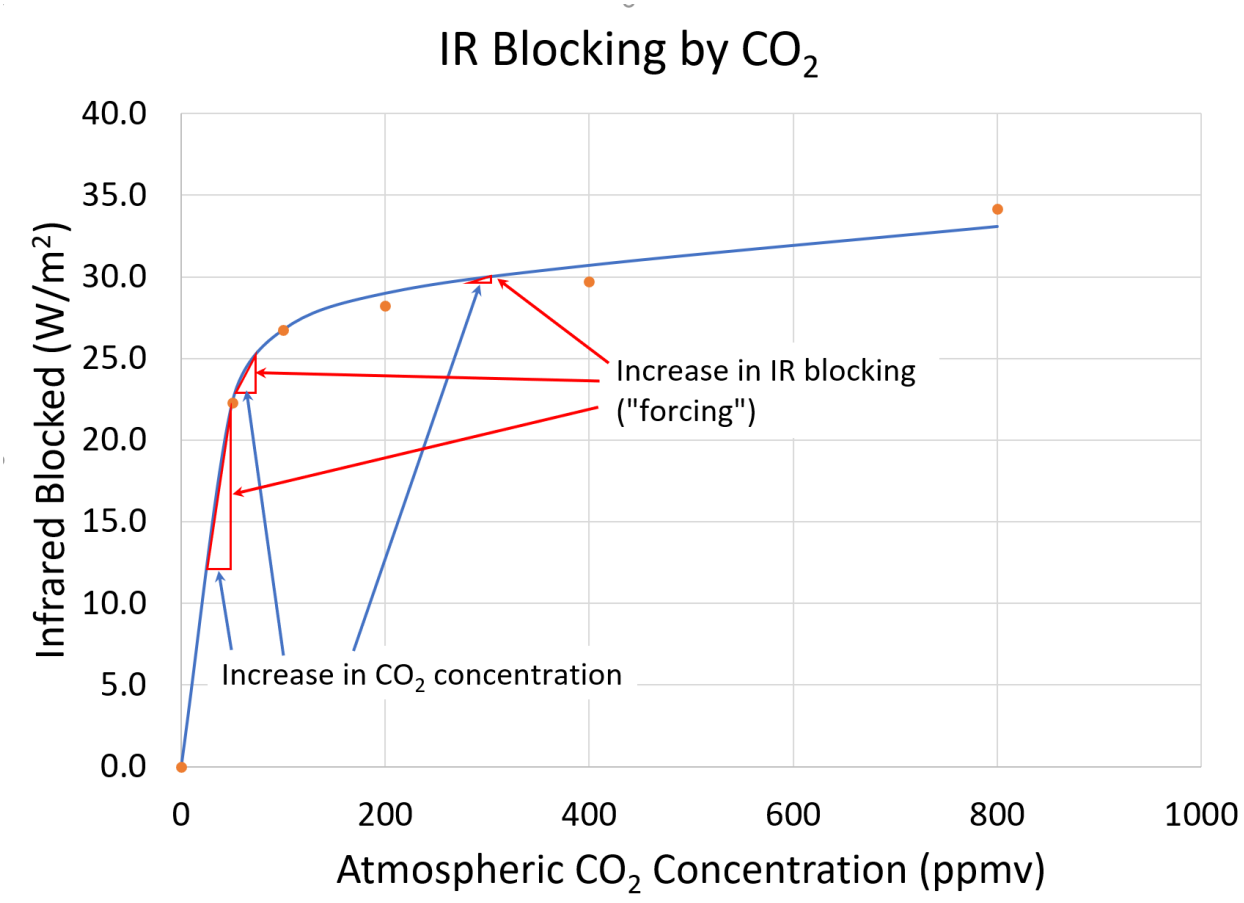


Figure 6: IR blocking for CO_2 concentrations from 0 to 800 ppmv. Given an increase in the CO_2 concentration, the effect decreases as the amount of atmospheric CO_2 increases.

Consequences

At this point, the reader may well be confused about the whole fuss about wavelengths. After all, the amount of IR blocking by CO_2 agrees with what was apparently well known when Siegel wrote his *Forbes* essay [3], and the amount of future IR blocking occasioned by doubling the CO_2 concentration agrees approximately with IPCC estimates. But failing to consider the spectrum leads to erroneous conclusions. Similarly, failing to distinguish between the surface of the earth and the earth as a whole is a failure to understand what happens.

To understand the physics, let us repeat that at equilibrium, the solar radiation absorbed by the earth will be exactly matched by the radiation emitted by the *earth as a whole*, namely 244 W/m². An increase in CO_2 concentration will necessarily decrease the amount of IR emitted in the CO_2 band, and will heat the surface somewhat. The warmed surface will radiate more IR *at all wavelengths*, allowing more IR to escape at other (non-CO_2) wavelengths. In other words, all other things remaining the same, the earth will still radiate 244 W/m² averaged over the entire globe out to space. In still other words, the effective blackbody temperature of the earth does not change. It remains at 255 K.

On the other hand, the *surface* of the earth will feel an increase in absorbed heat from a somewhat heated sky. What will be the effect?

The surface of the earth behaves like a blackbody, emitting 394 W/m² in a broad spectrum as shown in Figures 2, 3, and 4. How much would the temperature increase if the blackbody emitted 3.5 W/m² more (as specified in current models)?[3]

Again, we revert to basic physics. In equilibrium, the net energy received by the surface will equal the energy released by the surface, *mostly* by infrared radiation. (We will ignore the latent heat and sensible heat delivered to the atmosphere, as they are internal processes.) An additional 3.5 W/m² blocked by CO_2 in the atmosphere will be matched by an additional 3.5 W/m² radiated by the warmer surface.

The total radiative power (P) per unit area (A) of a blackbody is given by the Stefan-Boltzmann radiation law (See, for example, http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/stefan.html):

$$I = \frac{P}{A} = \sigma T^4 ,$$

where the intensity I is the radiant power per unit area, the temperature is in Kelvin, and the Stefan-Boltzmann constant σ is 5.67×10^{-8} (W/(m²K⁴)). For small changes (Δ), it is easier to use

$$\Delta I = 4\sigma T^3 \Delta T$$

The result for body at 288.7 K and an increase of 3.5 W/m², is a rise of 0.65 K (= 0.65 ºC).

Discussion

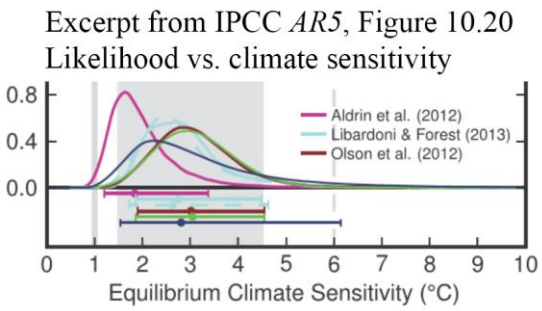
The greenhouse effect amounts to a blocking of 150 W/m² of IR from the surface, about 30 W/m² of which can be attributed to CO_2. The surface of the earth is 33 ºC (59ºF) warmer than it would be without an atmosphere (and if it had the same albedo, and it were all at the same temperature). Some 6.6 ºC (12 ºF) of that warming is due to CO_2.

A doubling of CO_2 concentration—adding as much CO_2 as we presently have, from our present 400 ppmv to 800 ppmv—would increase the blocking from 150 W/m² to 153.5 W/m². The "forcing" would cause the surface temperature to rise—all other things being equal— by 0.65 ºC (1.1 ºF). Well, that needs be corrected to account for the fact that 20% of the enhanced IR will be blocked. We add 25% to the 3.5 W/m², and get 4.375 W/m², with a corresponding temperature rise of 0.8 ºC (1.4 ºF). In other words, the warming that would be caused by the next 400 ppmv would be about one-tenth as much as caused by the first 400 ppmv. Again, this is likely an overestimate, as the calculations of Happer and van Wijngaarden show an increase in blocking of 2.5-3 W/m².

It is claimed (somewhat controversially) that the pre-industrial atmospheric CO_2 concentration was 290 ppmv. Figure 6 shows that the blocking effect from CO_2 due to the increase from 290 ppmv to the present 400 ppmv is about 1 W/m², for which the temperature rise would be less than 0.2 ºC. The temperature rise due to the increase in CO_2 concentration since the 70s—when the "experts" all clamored about an imminent ice age—would be even less.

Yet we know from satellite measurements that the temperature rise since about 1979 has been almost 0.6 ºC, far above that caused directly by CO_2.

Climate scientists are fully aware of these numbers. They know that increasing CO_2 concentration—by itself—has little effect on temperature even if the amount doubles. The claim is that the warming is amplified by the increase in the H_2O greenhouse effect. IPCC's "Equilibrium Climate Sensitivity" is the supposed rise in temperature due to a doubling of CO_2 concentration, and has been claimed for decades to lie between 1.5 ºC and 4.5 ºC, with a greatest likelihood of



3 ºC, about 4 times the 0.8 ºC of warming due to CO_2 alone. Without that amplification, "global warming" (a.k.a. "climate change") is a non-starter.

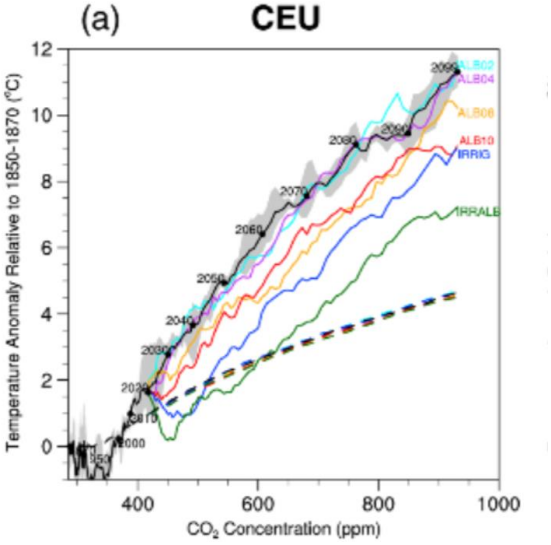
So, let us consider the amplification question. A small increase in temperature occasioned by an increase in CO_2 concentration supposedly causes a 4 × larger change in temperature because of H_2O (or some other hypothetical phenomenon). What's so special about CO_2? No climate scientist has proposed any kind of exotic (or common) chemical reactions involving CO_2, nor has anybody proposed any amplification caused by the relatively high molecular weight of CO_2. In fact, the *only* thing that supposedly fires up the amplification mechanism is the increase in temperature caused by increased CO_2. But increased temperature is increased temperature, regardless of the cause. Therefore, according to the IPCC and current climate models, anything whatsoever that causes the temperature to rise should cause exactly the same 4 × amplification of the temperature rise.

Anything whatsoever that causes the temperature to rise should cause exactly the same 4 × amplification of the temperature rise.

In case you are wondering why the earth did not bootstrap itself into boiling temperatures during the Eemian Interglacial, the Holocene Climate Optimum, the Minoan Warm Period, the Roman Warm Period, the Medieval Warm Period, or thousands of other warmings, the answer is that the climate is not controlled by positive feedback—where hot weather begets even hotter weather—but by negative feedback—where, as things get hotter, they shed more heat. For the last half-billion years, this negative feedback system has kept the temperature of the surface of the earth within a few percent of its present 288 K. The last 1.8-million years has been the Pleistocene Epoch, a series of 100,000-year glacial periods punctuated with short 10,000-15,000 interglacial periods like the present one. Whoops! The last 10,000 years has been called the Holocene, so the Pleistocene must be over. That's what the charts say. Whoops! It's now the Anthropocene! Stay tuned!

Perhaps the most important lesson to get from this discussion is that the heating effect of additional CO_2 gets smaller and smaller as the CO_2 concentration increases more and more. This shows up dramatically in Figures 1, 2, 3, and 6, and in the cutouts for the four CO_2 concentrations. The hysterical notion that things are going to get worse and worse because of CO_2 is very clearly at odds with the known properties of CO_2.

The figure to the right comes from the IPCC's 6th Assessment Report (*AR6*). The dashed line shows their projected Global Mean Temperature anomaly (difference from the 1850-1870 average, the "end" of the Little Ice Age), versus CO_2 concentration. (The other lines are projected highs.) By 800 ppmv, the projected rise is almost 4 ºC above the present temperature. It is funny how, as the influence of CO_2 gets smaller and smaller, the influence of CO_2 gets larger and larger. "Climate science" produces unbelievable results.



Hold onto your wallets as the classless political class attempts to "fight" ("battle," "address," "combat," "stop," "tackle," "reverse" …) "climate change."

We will end this essay somewhat like we began it, with pronouncements by self-styled arbiters of truth:

> Jonathan Shaw, "Controlling the Global Thermostat: Coming to terms with climate change's relentless, long-term fallout," *Harvard Magazine,* November-December 2020; Sarah Kaplan, "The undeniable link between weather disasters and climate change," *Washington Post*, 10/22/2020; Carolyn Gramling, "What's behind August 2020's extreme weather? Climate change and bad luck," *Science News*, 8/27/20; Priyanka Runwal, "Climate Change Hits Rock and Roll as Prized Guitar Wood Shortage Looms: Flooding and a

wood-boring beetle threaten supplies of storied "swamp ash," *Scientific American* October 28, 2020; A NOVA show (10/29/2020) implied "without evidence" (as the news media are wont to say) about a dozen things (wildfires, floods, droughts…), in rapid-fire video sequence, are caused by "climate change" caused by CO_2; Bruce Finley, "As Colorado wildfires burn, fears that climate change is causing 'multi-level emergency' mount: Heat, aridity, mega-fires and smoke are intensifying faster than projected," *Denver Post*, 10/25/20; The Dalai Lama "has co-authored a book about climate change called: *Our Only Home,"* NPR 11/11/20; "Warmer seas keep hurricanes stronger for longer, study says," msn.com, 11/20/20.

Appendix: Equations Used

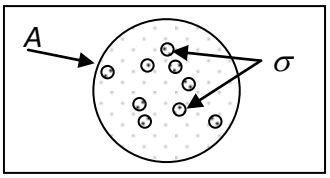
Area of circle = πR^2

Area of sphere = $4\pi R^2$

Average solar energy received by earth = average power radiated by earth

T (kelvins, K) = T (°C) + 275.15

The interaction between molecules and IR at some specified wavelength is characterized by "absorption cross-sections" [6]. Imagine looking up through a long tube whose cross-sectional area is A, and seeing N (gazillions) of molecules, each of which has an absorption cross-section of σ. The fractional intensity of the IR beam (at that wavelength is thus diminished.



$$\frac{dI}{I} = \frac{N\sigma}{A} = \frac{nV\sigma}{A} = nL\sigma \qquad n = \text{ \# per unit volume; } V = \text{ volume; L = distance}$$

$$\Rightarrow I = I_0 e^{-nL\sigma} \qquad \text{mean free path } L_{mean} = \frac{1}{n\sigma}$$

Number of molecules per unit volume is calculated from the Ideal Gas Law

$$PV = NkT \qquad k = \text{ Boltzmann constant} = 1.38\times10^{-23} \text{ J/K}$$

$$n = \frac{N}{V} = \frac{P}{kT} = \text{ (for sea level at 288.7 K) } \frac{1.01\times10^5 \text{ Pa}}{\left(1.38\times10^{-23} \text{ J/K}\right)(288.7 \text{ K})}$$

$$= 2.54\times10^{25} \text{ molecules per cubic meter.}$$

$$n_{CO2} = \left(400\times10^{-6}\right)\left(2.54\times10^{25}\right) \simeq 10^{22} \text{ } CO_2 \text{ molecules/m}^3 \text{ at 400 ppmv}$$

Radiant power per unit area emitted by "blackbody" = $I = \frac{P}{A} = \sigma T^4$ (Stefan-Boltzmann law)

Small changes: $\Delta I = 4\sigma T^3 \Delta T$

Stefan-Boltzmann constant: $\sigma = 5.67\times10^{-8} \ \frac{\text{W}}{\text{m}^2\text{K}^4}$

"Forcing" due to doubling $CO_2 = 5.05 \ \frac{\text{W}}{\text{m}^2} * \ln(2) = 3.5 \ \frac{\text{W}}{\text{m}^2}$ (used in latest climate models)

(The blackbody curves are from the Planck Distribution)

Planck Distribution (wavenumbers): $B(\hat{\nu},T) = 2hc^2\hat{\nu}^3 \frac{1}{e^{\frac{hc\hat{\nu}}{kT}} - 1}$

[6] Molecular IR absorption spectra available at the University of Washington website http://vpl.astro.washington.edu/spectra/VPLSpectra/frontpage.htm

The Author

Howard "Cork" Hayden, Professor Emeritus of Physics, University of Connecticut, retired to Pueblo West, Colorado.

Most of my research career involved accelerator-based atomic and molecular collisions. My first publication about energy was in 1981, and I wrote the seminal paper about computer simulations in April 1984: "A Computer Simulation of $F = m/a$." (Laugh.) In August 2020, I began the 25th year of publishing a monthly energy newsletter, *The Energy Advocate*.

When I learned about kilowatts and kilowatt-hours, the price for a kWh of electrical energy was 4 cents, and a candy bar was a nickel. Now electricity costs about 14 cents/kWh, and I'd need to take out a loan to buy a candy bar.

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