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A Saturated Gassy Argument

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The simple physics explanations for the greenhouse effect that you find on the internet are often quite wrong. These well-meaning errors can promote confusion about whether humanity is truly causing global warming by adding carbon dioxide to the atmosphere. Some people have been arguing that simple physics shows there is already so much CO_2 in the air that its effect on infrared radiation is "saturated"— meaning that adding more gas can make scarcely any difference in how much radiation gets through the atmosphere, since all the radiation is already blocked. And besides, isn't water vapor already blocking all the infrared rays that CO_2 ever would?

The arguments do sound good, so good that in fact they helped to suppress research on the greenhouse effect for half a century. In 1900, shortly after Svante Arrhenius published his pathbreaking argument that our use of fossil fuels will eventually warm the planet, another scientist, Knut Ångström, asked an assistant, Herr J. Koch, to do a simple experiment. He sent infrared radiation through a tube filled with carbon dioxide, containing somewhat less gas in total then would be found in a column of air reaching to the top of the atmosphere. That's not much, since the concentration in air is only a few hundred parts per million. Herr Koch did his experiments in a 30cm long tube, though 250cm would have been closer to the right length to use to represent the amount of CO_2 in the atmosphere. Herr Koch reported that when he cut the amount of gas in the tube by one-third, the amount of radiation that got through scarcely changed. The American meteorological community was alerted to Ångström's result in a commentary appearing in the June, 1901 issue of Monthly Weather Review, which used the result to caution "geologists" against adhering to Arrhenius' wild ideas.

Still more persuasive to scientists of the day was the fact that water vapor, which is far more abundant in the air than carbon dioxide, also intercepts infrared radiation. In the infrared spectrum, the main bands where each gas blocked radiation overlapped one another. How could adding CO_2 affect radiation in bands of the spectrum that H_2O (not to mention CO_2 itself) already made opaque? As these ideas spread, even scientists who had been enthusiastic about Arrhenius's work decided it was in error. Work on the question stagnated. If there was ever an "establishment" view about the greenhouse effect, it was confidence that the CO_2 emitted by humans could not affect anything so grand as the Earth's climate.

Nobody was interested in thinking about the matter deeply enough to notice the flaw in the argument. The scientists were looking at warming from ground level, so to speak, asking about the radiation that reaches and leaves the surface of the Earth. Like Ångström, they tended to treat the atmosphere overhead as a unit, as if it were a single sheet of glass. (Thus the "greenhouse" analogy.) But this is not how global warming actually works.

What happens to infrared radiation emitted by the Earth's surface? As it moves up layer by layer through the atmosphere, some is stopped in each layer. To be specific: a molecule of carbon dioxide, water vapor or some other greenhouse gas absorbs a bit of energy from the radiation. The molecule may radiate the energy back out again in a random direction. Or it may transfer the energy into velocity in collisions with other air molecules, so that the layer of air where it sits gets warmer. The layer of air radiates some of the energy it has absorbed back toward the ground, and some upwards to higher layers. As you go higher, the atmosphere gets thinner and colder. Eventually the energy reaches a layer so thin that radiation can escape into space.

What happens if we add more carbon dioxide? In the layers so high and thin that much of the heat radiation from lower down slips through, adding more greenhouse gas molecules means the layer will absorb more of the rays. So the place from which most of the heat energy finally leaves the Earth will shift to higher layers. Those are colder layers, so they do not radiate heat as well. The planet as a whole is now taking in more energy than it radiates (which is in fact our current situation). As the higher levels radiate some of the excess downwards, all the lower levels down to the surface warm up. The imbalance must continue until the high levels get hot enough to radiate as much energy back out as the planet is receiving.

Any saturation at lower levels would not change this, since it is the layers from which radiation does escape that determine the planet's heat balance. The basic logic was neatly explained by John Tyndall back in 1862: "As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial [infrared] rays, produces a local heightening of the temperature at the Earth's surface."

Even a simple explanation can be hard to grasp in all its implications, and scientists only worked those out piecewise. First they had to understand that it was worth the trouble to think about carbon dioxide at all. Didn't the fact that water vapor thoroughly blocks infrared radiation mean that any changes in CO_2 are meaningless? Again, the scientists of the day got caught in the trap of thinking of the atmosphere as a single slab. Although they knew that the higher you went, the drier the air got, they only considered the total water vapor in the column.

The breakthroughs that finally set the field back on the right track came from research during the 1940s. Military officers lavishly funded research on the high layers of the air where their bombers operated, layers traversed by the infrared radiation they might use to detect enemies. Theoretical analysis of absorption leaped forward, with results confirmed by laboratory studies using techniques orders of magnitude better than Ångström could deploy. The resulting developments stimulated new and clearer thinking about atmospheric radiation.

Among other things, the new studies showed that in the frigid and rarified upper atmosphere where the crucial infrared absorption takes place, the nature of the absorption is different from what scientists had assumed from the old sea-level measurements. Take a single molecule of CO_2 or H_2O. It will absorb light only in a set of specific wavelengths, which show up as thin dark lines in a spectrum. In a gas at sea-level temperature and pressure, the countless molecules colliding with one another at different velocities each absorb at slightly different wavelengths, so the lines are broadened and overlap to a considerable extent. Even at sea level pressure, the absorption is concentrated into discrete spikes, but the gaps between the spikes are fairly narrow and the "valleys" between the spikes are not terribly deep. (see **Part II**) None of this was known a century ago. With the primitive infrared instruments available in the early 20th century, scientists saw the absorption smeared out into wide bands. And they had no theory to suggest anything different.

Measurements done for the US Air Force drew scientists' attention to the details of the absorption, and especially at high altitudes. At low pressure the spikes become much more sharply defined, like a picket fence. There are gaps between the H_2O lines where radiation can get through unless blocked by CO_2 lines. Moreover, researchers had become acutely aware of how very dry the air gets at upper altitudes — indeed the stratosphere has scarcely any water vapor at all. By contrast, CO_2 is well mixed all through the atmosphere, so as you look higher it becomes relatively more significant. The main points could have been understood already in the 1930s if scientists had looked at the greenhouse effect closely (in fact one physicist, E.O. Hulbert, did make a pretty good calculation, but the matter was of so little interest that nobody noticed.)

As we have seen, in the higher layers where radiation starts to slip through easily, adding some greenhouse gas must warm the Earth regardless of how the absorption works. The changes in the H_2O and CO_2 absorption lines with pressure and temperature only shift the layers where the main action takes place. You do need to take it all into account to make an exact calculation of the warming. In the 1950s, after good infrared data and digital computers became available, the physicist Gilbert Plass took time off from what seemed like more important research to work through lengthy calculations of the radiation balance, layer by layer in the atmosphere and point by point in the spectrum. He announced that adding CO_2 really could cause a degree or so of global warming. Plass's calculations were too primitive to account for many important effects. (Heat energy moves up not only by radiation but by convection, some radiation is blocked not by gas but by clouds, etc.) But for the few scientists who paid attention, it was now clear that the question was worth studying. Decades more would pass before scientists began to give the public a clear explanation of what was really going on in these calculations, drawing attention to the high, cold layers of the atmosphere. Even today, many popularizers try to explain the greenhouse effect as if the atmosphere were a single sheet of glass.

In sum, the way radiation is absorbed only matters if you want to calculate the exact degree of warming — adding carbon dioxide will make the greenhouse effect stronger regardless of saturation in the lower atmosphere. But in fact, the Earth's atmosphere is not even close to being in a state of saturation. With the primitive techniques of his day, Ångström got a bad result, as explained in the **Part II** . Actually, it's not clear that he would have appreciated the significance of his result even if he had gotten the correct answer for the way absorption varies with CO_2 amount. From his writing, it's a pretty good guess that he'd think a change of absorption of a percent or so upon doubling CO_2 would be insignificant. In reality, that mere percent increase, when combined properly with the "thinning and cooling" argument, adds 4 Watts per square meter to the planets radiation balance for doubled CO_2. That's only about a percent of the solar energy absorbed by the Earth, but it's a highly important percent to us! After all, a mere one percent change in the 280 Kelvin surface temperature of the Earth is 2.8 Kelvin (which is also 2.8 Celsius). And that's without even taking into account the radiative forcing from all those amplifying feedbacks, like those due to water vapor and ice-albedo.

In any event, **modern measurements** show that there is not nearly enough CO_2 in the atmosphere to block most of the infrared radiation in the bands of the spectrum where the gas absorbs. That's even the case for water vapor in places where the air is very dry. (When night falls in a desert, the temperature can quickly drop from warm to freezing. Radiation from the surface escapes directly into space unless there are clouds to block it.)

So, if a skeptical friend hits you with the "saturation argument" against global warming, here's all you need to say: (a) You'd still get an increase in greenhouse warming even if the atmosphere were saturated, because it's the absorption in the thin upper atmosphere (which is unsaturated) that counts (b) It's not even true that the atmosphere is actually saturated with respect to absorption by CO_2, (c) Water vapor doesn't overwhelm the effects of CO_2 because there's little water vapor in the high, cold regions from which infrared escapes, and at the low pressures there water vapor absorption is like a leaky sieve, which would let a lot more radiation through were it not for CO_2, and (d) These issues were satisfactorily addressed by physicists 50 years ago, and the necessary physics is included in all climate models.

Then you can heave a sigh, and wonder how much different the world would be today if these arguments were understood in the 1920's, as they could well have been if anybody had thought it important enough to think through.

For Further Reading

References and a more detailed history can be found **here** and **here**.

Some aspects of the "thinning and cooling" argument, and the importance of the radiating level are found in the post **A Busy Week for Water Vapor**, which also contains a discussion of water vapor radiative effects on the top-of-atmosphere vs. surface radiation budget. A general discussion of the relative roles of water vapor and CO_2 is given in **Gavin's post** on ths subject.

You can get a good feel for the way CO_2 and water vapor affect the spectrum of radiation escaping the Earth by playing around with Dave Archer's online radiation model **here**. It would help, of course, to read through the explanation of radiating levels in Archer's book, **Understanding the Forecas**t. A discussion of radiating levels for real and idealized cases, at a more advance level, can be found in the draft of Pierrehumbert's **ClimateBook**; see Chapters 3 and 4.

The Monthly Weather Review article commenting on Ångström's work is **here**, and Ångström's original article is **here**.