Is the CO2 effect saturated?

What The Science Says:
This argument originates from Angstrom's work in 1901. We now know that the planetary energy balance is determined by the upper levels of the troposphere and that the saturation of the absorption at the central frequency does not preclude the possibility to absorb more energy.

Climate Myth: CO2 effect is saturated
"Each unit of CO2 you put into the atmosphere has less and less of a warming impact. Once the atmosphere reaches a saturation point, additional input of CO2 will not really have any major impact. It's like putting insulation in your attic. They give a recommended amount and after that you can stack the insulation up to the roof and it's going to have no impact." (Marc Morano, as quoted by Steve Eliot)

After the famous Arrhenius paper in 1896, where he did the first calculations of the CO2 greenhouse effect, his theory was dismissed by Angstrom with a simple experiment. He let an infrared beam pass through a tube filled with CO2 and measured the emerging light intensity. Upon reducing CO2 concentration in the tube, only a tiny difference could be found and he concluded that very few CO2 molecules are enough to completely absorb the IR beam. The conclusion was that a CO2 increase could not matter. This was the birth of the first skeptic of the then called "CO2 theory" and of the more recent "CO2 effect is saturated" skeptic argument.

Thirty years later, E. O. Hulburt (Phys. Rev. 38, 1876–1890 (1931)) added convection to the purely radiative equilibrium assumed by Arrhenius. He found that convective equilibrium holds in the lower part of the troposphere up to about 10 Km, while radiative holds equilibrium above. The important consequence is that the details of the absorption in the lower troposphere do not matter since heat "is spread around and transferred upward by convection". In other words, what govern the energy balance of the earth is the radiative balance in the upper troposphere and CO2 concentration there does matter.

Hulburt was very prudent in his conclusions:

> *"The agreement is no doubt better than is warranted by the accuracy of the data on which the calculations are based. Apparently the uncertainties and omissions have conspired to counteract each other to some extent."*

Nevertheless, his work is definitely a milestone in the understanding of our atmosphere.

Hulburt's work should have put the controversy on the CO2 theory to an end, since "objections which have been raised against it by some physicists are not valid". Unfortunately, this paper passed almost unnoticed, I guess because meteorologists and geologists do not read Physical Review so often.

At the time of Hulburt the CO2 absorption coefficient was not known very accurately and even less its line shape, forcing Huburt to use a "box-like" shape. We may now build a simple model with a more realistic line shape and show that we get an increased absorption with increasing CO2 concentration anyways.

Consider the CO2 absorption band around 15 µm (about 650 cm-1), it is strong enough to not let any light go through after a few tens of meters at surface temperature and pressure. Did this energy disappear forever? Surely not, radiatively or convectively this energy "is spread around and transferred upward". But on the way up this light will find a decreasing pressure, i.e. less CO2 molecules. There will be a point where the light can escape to the outer space. The intensity of the emerging light will be appropriate for the temperature of this "last" layer layer.

We can crudely model this behavior using the Plank law and a gaussian-shaped absorption coefficient. We consider just two layers, the surface and the "last" layer, and the emissivity of this outer layer is modulated between 0 and 1 according to the absorption coefficient α. The result is shown in the figure below.

In the calculations I used an absorption wavenumber of 650 cm-1 and tuned the optical depth to reach saturation. The two dashed lines correspond to the Plank law for T=300 K and T=220 K. The red curve is the calculated emission; it follows the 300 K curve but deviates from it near the absorption band. This dip represents the energy prevented to reach the outer space, i.e. the greenhouse effect.

This graph can be *qualitatively* compared with real measurements to be sure we're not too far off.

We can now look at what happens when we increase α. Following Angstrom (and many others in his times) the energy absorbed should not change. On the contrary, if we recall that the absorption coefficient is gaussian we would expect an increase in the energy retained by our layer along the wings. The effect is shown in the figure below.

We can see that although the absorption dip cannot fall below the 220 K curve, it becomes wider and the absorbed energy increases accordingly. This is as far as we can get with this simple model. Needless to say that there's much more than what can be done with the very crude model presented here. We know, for example, that the line shape of the absorption coefficient changes with both pressure and temperature due to what are called pressure and Doppler broadening. In the upper layers of the atmosphere the band initially gets narrower and then splits into several narrow bands (the roto-vibrational spectrum) leaving more room for the increase in CO_2 concentration being more effective. We also know that there are weaker absorption peaks other than the stronger one quoted above which are not saturated.

Gilbert Plass in 1956 used these words:

> *One further objection has been raised to the carbon dioxide theory: the atmosphere is completely opaque at the center of the carbon dioxide band and therefore there is no change in the absorption as the carbon dioxide amount varies. This is entirely true for a spectral interval about one micron wide on either side of the center of the carbon dioxide band. However, the argument neglects the hundreds of spectral lines from carbon dioxide that are outside this interval of complete absorption. The change in absorption for a given variation in carbon dioxide amount is greatest for a spectral interval that is only partially opaque; the temperature variation at the surface of the Earth is determined by the change in absorption of such intervals.*

There's one more subtle effect related to increased absorption. Upon increasing CO_2 concentration, the layer at which the absorption coefficient at each wavelength is low enough to let the IR light escape will be found higher in the atmosphere. The emitting layer will then have a lower temperature, at least until the tropopause is reached, and hence a lower emitting power.

Clearly there's a world behind the absorption of IR light by CO_2 in the atmosphere which I omitted. The physics behind it is now solid thanks to the decades of work of many different scientists, and despite the first highly respected skeptic ever who put the CO_2 theory on hold for half a century. But you know, this is how science works.

Note: I cannot conclude without acknowledging the fundamental role of Spencer Weart "The Discovery of Global Warming" from which I borrowed (and learned) a lot. His book and the supporting website are a treasure cove for anyone interested in how our current knowledge has been built step by step over time.

Skeptical Science explains the science of global warming and examines climate misinformation through the lens of peer-reviewed research. The website won the Australian Museum 2011 Eureka Prize for the Advancement of Climate Change Knowledge. Members of the Skeptical Science team have authored peer-reviewed papers, a college textbook on climate change and the book Climate Change Denial: Heads in the Sand. Skeptical Science content has been used in university courses, textbooks, government reports on climate change, television documentaries and numerous books.