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Mini Review

# How Increased $CO_2$ Warms the Earth–Two Contexts for the Greenhouse Gas Effect

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## Abstract

The widespread explanations of the greenhouse effect taught to millions of schoolchildren are misleading. The objective of this work is to clarify how increasing $CO_2$ produces warming in current times. It is found that there are two contexts for the greenhouse gas effect. In one context, the *fundamental greenhouse gas effect*, one imagines a dry Earth starting with no water or $CO_2$ and adding water and $CO_2$. This leads to the familiar "thermal blanket" that strongly inhibits IR transmission from the Earth to the atmosphere. The Earth is much warmer with $H_2O$ and $CO_2$. In the other context, the *current greenhouse gas effect*, $CO_2$ is added to the current atmosphere. The thermal blanket on IR radiation hardly changes. But the surface loses energy primarily by evaporation and thermals. Increased $CO_2$ in the upper atmosphere carries IR radiation to higher altitudes. The Earth radiates to space at higher altitudes where it is cooler, and the Earth is less able to shed energy. The Earth warms to restore the energy balance. The "thermal blanket" is mainly irrelevant to the *current greenhouse gas effect*. It is concluded that almost all discussions of the greenhouse effect are based on the *fundamental greenhouse gas effect*, which is a hypothetical construct, while the *current greenhouse gas effect* is what is happening now in the real world. Adding $CO_2$ does not add much to a "thermal blanket" but instead, drives emission from the Earth to higher, cooler altitudes.

## Introduction

### Background

Were it not for the Sun, the Earth would be a frozen hulk in space. The Sun sends a spectrum of irradiance to the Earth, the Earth warms, and the Earth radiates energy out to space. This process continues until the Earth warms enough to radiate about as much energy to space as it receives from the Sun, reaching an approximate steady state. If for some reason, the Earth is unable to radiate all the energy received from the Sun, the Earth will warm until it can radiate all the energy received.

It is widely accepted that rising $CO_2$ concentration reduces the ability of the Earth to radiate energy to space. In a dynamic situation where the $CO_2$ concentration is continually increasing with time, the Earth will continuously warm as it tries to "catch up" to the effect of increasing $CO_2$ and reestablish a steady state. It is a conundrum that while it is widely accepted that rising $CO_2$ concentration produces global warming, the exact mechanism by which warming is induced in the current atmosphere by rising $CO_2$ is not widely understood. The concept of a "thermal blanket" imposed by greenhouse gases to warm the Earth has merit in some contexts but is mainly irrelevant to the question of how adding $CO_2$ to the current atmosphere produces warming.

Before attempting to deal with the question of how rising $CO_2$ concentration affects the current Earth's climate, it is appropriate to first discuss the Earth's energy budget. The exact values for each energy flow are not important, but the relative values are important to show which processes dominate.

Finally, we provide an explanation of how adding $CO_2$ to the current atmosphere produces global warming in the current atmosphere. The mechanism is not widely known and is likely to be surprising to some. Warming does not occur by increasing the thickness of the thermal blanket but instead occurs by raising the altitude at which the Earth radiates to space.

### Solar energy input to the earth

Estimates of energy transfer in the Earth system were made by Lindsey, Trenberth, et al. Wild, et al. and Stephens, et al. [1-4]. In the manuscript that follows, the results of these studies are interpreted and averaged to provide a rough summary of the Earth's energy budget. The exact values of the various energy flows are not important in this study, but their relative magnitudes are important to define the major mechanisms for energy flow. These four references will be referred to generically as "LTWS". Godwin also reviewed these references, but he reached very different conclusions than are reached in this manuscript [5].

LTWS is widely agreed that the average solar power input to Earth is 341 W/m$^2$. The solar irradiance in the upper atmosphere is about 1,362 W/m$^2$ [6]. The LTWS models hypothesize 1,362 W/m$^2$ of solar power impinging on a column of the radius of the Earth (R) with the cross-sectional area $\pi R^2$, while the total area of the Earth is $4\pi R^2$, so the average solar intensity on the Earth is (1/4) (1,362 W/m$^2$). That is how they might have derived 341 W/m$^2$ as the average solar input to the Earth.

Based on LTWS, solar power input to Earth was interpolated and averaged to be approximately distributed as follows:

Input to Earth: 341 W/m$^2$

Reflected by the atmosphere (and returned to space) 79 W/m$^2$

Reflected by the Earth's surface (and returned to space) 23 W/m$^2$

Total injected into the Earth system = 341 – 79 – 23 = 239 W/m$^2$

Absorbed by the Earth's lower atmosphere 76 W/m$^2$

Absorbed by the Earth's surface 163 W/m$^2$

These inputs from the Sun to Earth are used as starting points for analyzing energy flow within the Earth system.

## IR radiation

A fundamental law of physics states that all bodies emit a spectrum of radiant power proportional to the fourth power of their absolute temperature. A body at absolute temperature T (K) emits power per unit area:

$$P = \sigma T^4 = 5.67 \times 10^{-8} T^4 \text{ (W/m}^2\text{)}$$

For example, a body at T = 280 K is said to emit 348 W/m$^2$.

However, this law of physics is academic and not directly applicable to real-world experience. In the real world, we never have a single isolated body emitting radiation, instead, we deal with pairs of bodies where the warmer one radiates a net flux to the cooler one. (If you stand next to a body at 280 K, you don't feel an incoming heat flux of 348 W/m$^2$). For example, if there is one body at 280 K and a second body at 275 K, the warmer body will radiate through a vacuum to the cooler body at a net of 24 W/m$^2$. That is a real-world parameter that can be measured. But the academic model involves calculating the emission of the warm body as 348 W/m$^2$ and the emission of the cooler body as 324 W/m$^2$, and subtracting, the net transfer from the warm body to the cool body is 24 W/m$^2$. But the calculated values are academic and cannot be measured in the real world with 348 W/m$^2$ in one direction and 324 W/m$^2$ in the opposite direction. Those values are only of academic use to infer the measurable net of about 24 W/m$^2$. See the simple model in Figure 1 presented here for illustration.

Next, consider the case where an IR-absorbing gas is placed between the two radiating bodies as shown on the right side of Figure 2. In the left side of the figure, there are two plates radiating from one another through a vacuum with the warm plate delivering a net of 215.7 W/m$^2$ to the colder plate. On the right side of Figure 2, the space between the plates is filled with an IR-absorbing gas. The molecules that absorb radiant energy, reemit energy in all directions, including back toward the hotter plate. The higher the density of gas, the less radiant energy gets through to the cold plate. The actual amount of IR radiation that reaches the colder plate depends on the opacity of the IR-absorbing gas. In Figure 2; 25 W/m$^2$ was arbitrarily inserted for illustration of a very opaque gas.

It should also be noted that the plates emit a characteristic spectrum of IR wavelengths for their temperatures, and if the IR-absorbing gas does not absorb a part of the spectrum, that part of the spectrum will pass through the gas as easily as if it were a vacuum.

In the sections that follow, the surface of the Earth can be regarded as the warm plate and a high altitude in the atmosphere can be regarded as the cold plate with gas in between that absorbs most of the IR radiation and passes some IR radiation.

## The two contexts of the greenhouse effect

We are all aware of the widely discussed greenhouse effect

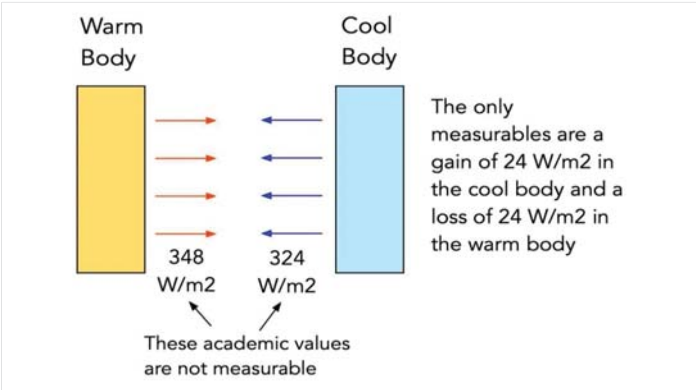


**Figure 1:** Radiant heat transfer between warm and cool bodies.

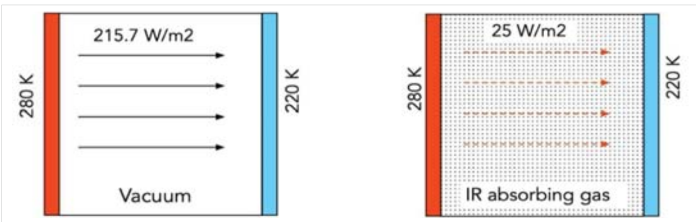


**Figure 2:** Radiant heat transfer from warm plate to cold plate separated by vacuum or separated by IR absorbing gas.

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that warms the Earth as the concentration of greenhouse gases increases. But just how does it work?

Here, we define two contexts for greenhouse gas effects:

1) The *fundamental greenhouse gas effect* can be described by a "gedanken experiment" in which one imagines a dry Earth starting with no water or $CO_2$ and begins adding water and $CO_2$. The original atmosphere, lacking water and $CO_2$, will transmit IR radiation completely. As a result, the Earth will be quite cool. As $H_2O$ and $CO_2$ are added to the atmosphere, the transmission of IR radiation from the Earth's surface is increasingly inhibited, and the Earth warms. As the Earth warms, evaporation and thermals transmit more energy from the Earth to the atmosphere. By the time $H_2O$ and $CO_2$ levels reach current levels, the atmosphere is almost opaque to IR radiation, and a "thermal blanket" greatly reduces IR transmission from the Earth to the atmosphere. The Earth cools primarily by evaporation and thermals, and it is much warmer than if $CO_2$ and water were absent. The notion of a "thermal blanket" of IR absorbing gases warming the Earth has validity in this context starting with a transmitting atmosphere and adding greenhouse gases. However, once the thermal blanket is established with ~ 400 ppm $CO_2$, adding more $CO_2$ has only a small effect on reducing IR radiation from the surface.

2) The *current greenhouse gas effect* deals with the question: How does the addition of $CO_2$ to the atmosphere affect the global average temperature in 2024 and beyond, with $CO_2$ around 400+ ppm? It was shown previously that starting with no water or $CO_2$, adding $H_2O$ and $CO_2$ to the atmosphere generates a "thermal blanket" for radiation. But once that "thermal blanket" is well established and the lower atmosphere is very opaque to IR radiation, what is the effect of adding even more $CO_2$? Dufresne, et al. provide a detailed technical analysis to show how the current greenhouse effect works [7]. However, this reference is complex and written for expert specialists in IR transmission through the atmosphere. In the sections that follow, a simpler, qualitative interpretation will be presented.

## Energy budget of the earth

Energy transfer in the Earth system can take place by thermal transfers ("thermals") where winds carry warm air up to colder regions, evaporation from the surface (removes heat), and condensation in the atmosphere (deposits heat) and radiation (further discussion follows).

After analyzing the data in the LTWS references (see Section 1.2), a rough estimate of key energy flows per unit time in the Earth system is given as follows. The exact numbers are not critical; only their relative values are important for this discussion.

Upward power flow from the surface:

Thermals (warm air transported upward) 18 $W/m^2$

Evaporation from the surface and condensation in the atmosphere 80 $W/m^2$

Radiation to the atmosphere 25 $W/m^2$ (note: some estimates are as high as 50 $W/m^2$)

Radiation through IR window to space 40 $W/m^2$

Total power from surface = 163 $W/m^2$

Received by the lower atmosphere:

Incoming solar irradiance absorbed 76 $W/m^2$

Thermals (from Earth) 18 $W/m^2$

Condensation 80 $W/m^2$

Radiation (from Earth) 25 $W/m^2$

Total = 199 $W/m^2$

Upper atmosphere:

Radiation (from Earth) through the window to space 40 $W/m^2$

Radiation from lower atmosphere 199 $W/m^2$

Total radiation emitted to space 239 $W/m^2$

Total power emanating from Earth to space = 239 + 79 + 23 = 341 $W/m^2$

These results can be visualized in Figure 3 which is based on the references LTWS.

As shown in Figure 3, incoming solar irradiance (341 $W/m^2$) is partly reflected by the lower atmosphere back out to

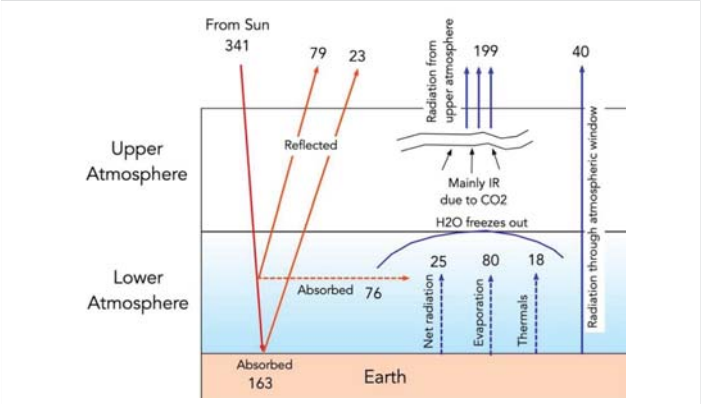


Figure 3: Energy flows in the Earth's system. (Based on LTWS references).

space (79 W/m$^2$), partly reflected by the Earth's surface back out to space (23 W/m$^2$), partly absorbed by the lower atmosphere (76 W/m$^2$), and finally about 163 W/m$^2$ is absorbed by the surface.

The Earth's surface emits the 163 W/m$^2$ that it absorbs as follows:

40 W/m$^2$ is radiated to space through a window in the absorption spectra of $H_2O$ and $CO_2$

18 W/m$^2$ is transmitted by thermals to the lower atmosphere

80 W/m$^2$ is transported to the lower atmosphere by evaporated water

25 W/m$^2$ is the net radiative transfer from the surface to the lower atmosphere through the optically thick $CO_2$ and $H_2O$ (as visualized on the right side of Figure 2). (Note that some references use a higher value).

Radiation from the Earth's surface to the lower atmosphere requires further discussion. The LTWS references show high up and down radiation flows. For example, Trenberth, et al. did not show radiation transfer between the Earth's surface as a simple 25 W/m$^2$ net radiative transfer from the surface to the lower atmosphere. Instead, they showed 356 W/m$^2$ radiated upward from the surface and 333 W/m$^2$ of "back radiation" from the atmosphere to the surface [2]. The figure 356 W/m$^2$ radiated upward from the surface corresponds to the theoretical radiation from a blackbody at 281.5 K. The claimed downward figure is difficult to explain. But both of these figures are academic. What is happening is that the warm Earth is radiating upward through an optically thick gas of $H_2O$ and $CO_2$ absorbers, and the radiant transfer through that thick gas is estimated to be only a mere ~25 W/m$^2$. This is the "thermal blanket" so often referred to in discussions of global warming. The thermal blanket is real. But the problem with so many discussions of the greenhouse effect is that there is a preoccupation with radiant energy transfer between the Earth and the atmosphere (which is "blanketed") while neglecting the more important transfers of energy to the atmosphere by processes other than radiation.

The terms "lower atmosphere" and "upper atmosphere" are defined next. Following Miscolczi, Figure 4 shows that the demarcation between upper and lower atmospheres occurs at an altitude of roughly 12 km above which $H_2O$ is frozen out and the temperature roughly stabilizes [8]. Energy transfer in the lower atmosphere takes place by conduction, convection, and radiation. Energy transfer in the upper atmosphere takes place primarily by radiation.

The lower atmosphere receives energy by absorption of incoming solar irradiance, and thermals, evaporation, and

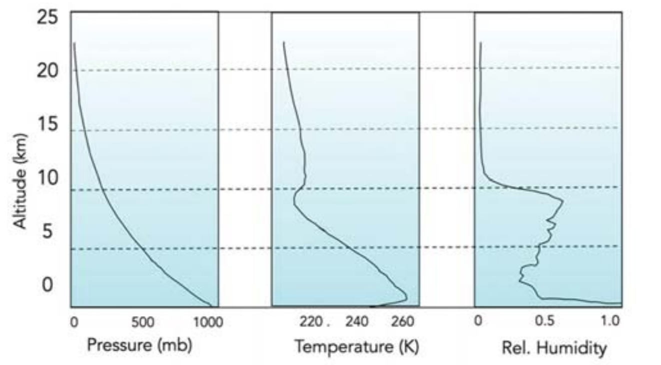


**Figure 4:** Pressure, temperature, and relative humidity vs. altitude [8].

radiation from the Earth's surface. In the upper atmosphere, energy transfer is primarily by radiation, propagated by the residual $CO_2$ concentration (water is frozen out). Over a range of higher altitudes, the upper atmosphere radiates energy to space.

## The greenhouse effect

The greenhouse effect can only be fully understood by comprehensive modeling of upward energy flows in the Earth system. Excellent studies by Dufresne, et al. and Pierrehumbert provide detailed physics [7,9]. Here, we interpret these results qualitatively.

The Earth is surrounded by cold space. The Earth receives solar radiation from the Sun, this energy is absorbed in the atmosphere, at the surface, in the oceans, and clouds. The Earth becomes warmer than its surroundings and radiates energy away to space. This continues until the Earth radiates about as much energy per unit of time as it receives from the Sun. It then remains relatively stable thermally. If for any reason, the Earth is unable to radiate all the energy per unit time it receives, it will warm.

Within the Earth system of land, ocean, atmosphere, and clouds, energy transfer is taking place continuously. There is a net energy flow upward toward higher altitudes. From the surface of the Earth, much of the upward flow of energy in the lower atmosphere is through evaporation and convection. The lower atmosphere is almost opaque to IR radiation due to water vapor and $CO_2$.

At higher altitudes, the atmosphere is colder and thins out, water vapor is frozen out, and convection no longer occurs, and radiation becomes the dominant means of energy transfer. IR radiation will be propagated if there is sufficient $CO_2$. Radiation energy transfer will persist out toward a high altitude until the $CO_2$ concentration diminishes. Each $CO_2$ molecule that absorbs an IR photon can reradiate in all directions, but in a thin atmosphere, some upward IR radiation will be lost, and on a net basis, this allows the Earth to radiate out to space. The presence of an IR transmitting/absorbing gas ($CO_2$) will allow energy transport to higher altitudes. The highest altitude where there is enough thin gas to maintain radiation is the region of the atmosphere that mainly radiates energy outward to space. This is illustrated on the left side of Figure 5. Figure 5 was created here to illustrate how the predominant energy transfer mechanisms gradually change to IR radiation at higher altitudes, and the presence of $CO_2$ carries the IR radiation to higher altitudes.

If the $CO_2$ content of the atmosphere is increased, there will be a higher concentration of $CO_2$ molecules in the upper atmosphere (at the same density), and IR radiant energy flow will persist up to a higher altitude. The region that radiates to space will be at higher altitudes (where it is colder) and by the radiation law, the Earth will not be able to radiate as much energy per unit time. The Earth and the atmosphere will warm until the region of emission is warm enough to radiate all the solar input to Earth out to space. This is illustrated on the right side of Figure 5.

As Lindzen pointed out, the lower atmosphere is opaque to IR radiation, and the surface of the Earth loses heat by convection, particularly cumulonimbus towers in the tropics [10]. At higher altitudes, the density decreases significantly, and IR transmission becomes the dominant means of energy transfer. This region of the atmosphere can radiate energy from the Earth to space. So, there is a lower atmosphere in which energy is transferred mainly by convection, topped by a higher atmosphere with decreasing density with altitude, where IR transmission gradually becomes the main means of energy transfer. The Earth loses energy by radiating from this upper level.

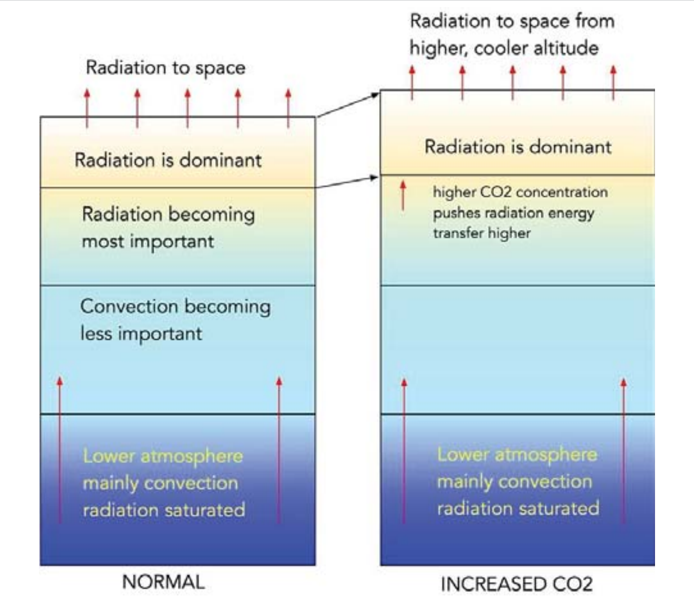


**Figure 5:** Qualitative sketch to show radiation is dominant at the highest altitude. By adding CO2 to the atmosphere, radiative energy transport is carried to a higher altitude where it is colder, reducing the radiant power emitted by the upper atmosphere.

Serious analysts of the *current greenhouse gas effect* agree that warming is mainly due to the increased $CO_2$ extending the region of radiative energy transfer in the upper atmosphere to higher altitudes, resulting in the emission of energy from a higher altitude where it is cooler [7,9]. The "thermal blanket" imposed by a nearly IR-opaque lower atmosphere only contributes about 10% to the *current greenhouse gas effect* [7].

## Author's perspective and future research directions

It is widely believed that greenhouse gases warm the Earth via an IR radiation "thermal blanket". Yet, as we have shown, the addition of more $CO_2$ to the atmosphere at present with a $CO_2$ concentration > 400 ppm does not produce significant warming by thickening the blanket. Instead, analysis indicates that adding $CO_2$ to the present atmosphere raises the altitude where the Earth radiates to space and that is the source of the current greenhouse effect. It is my experience that > 99% of all discussions of the greenhouse effect miss this important point, and I suspect that even most climate scientists don't understand this. We have a situation where the majority of the world believes that the greenhouse gas effect is warming the world, and this poses a threat to humanity. The U.N. and many of the world's nations have taken steps at great cost and risk to reduce future $CO_2$ emissions, yet they fail to understand the underlying mechanism of the current greenhouse effect. The proper understanding of the current greenhouse effect rests on a few published papers [7,9,10]. These analyses need to be expanded and developed further, and promulgated in the literature, along with a more comprehensive understanding of how factors other than greenhouse gases affect climate change. Our policies should be based on a more solid foundation of understanding of the underlying physics.

As the 21st century progresses, the Earth will likely warm further – primarily dependent on the levels of future $CO_2$ emissions, but other factors also enter into the total picture (land use, solar variations, ocean currents, volcanoes, etc.). Future energy demand will increase significantly and the world will try to reduce emissions through expanded use of renewable sources. Since the U.N. baseline year of 2015, global annual $CO_2$ emissions increased by about 6% despite the expansion of renewable energy usage. The people of the Earth will face a long, difficult challenge to reduce $CO_2$ emissions in the 21st century. The global average temperature will rise as cumulative emissions increase [11]. Expanded use of nuclear power and consumption of natural gas will be necessary but probably not sufficient. Natural gas should be a vital part of any plan to transition to low emissions since it emits $2H_2O$ for each $CO_2$ when it is burned. Yet, the Internet is rife with reports on US President Biden's "War on Natural Gas" – a giant step backward in the attempt to reduce global warming.

Finally, a major unknown in the matter of climate change is the question of what are the impacts on human life at any level of $CO_2$ concentration in the atmosphere. There is a tendency for politicians, media, and even climate scientists to attribute every storm, every drought, every flood, and every heat wave in 2024 to increased $CO_2$. Pielke published numerous papers and weekly postings on his website that analyze current impacts against historical impacts, taking proper allowance for demographic and financial differences between the present and the past, and generally, he finds these claims to be spurious. This does not mean that impacts due to greenhouse gases won't occur. It just means that we have not observed them yet [12].

## Conclusion

There are two different contexts for discussion of the effect of greenhouse gases on the Earth's climate.

In one context, one can imagine an Earth with no water vapor or $CO_2$ in the atmosphere. This Earth can radiate effectively to space and is relatively cold. As water vapor and $CO_2$ are added to the atmosphere, the IR-opacity of the atmosphere increases and the Earth system warms. The greenhouse gases act as a "thermal blanket" to warm the Earth by impeding upward IR radiation. This is labeled the *fundamental greenhouse gas effect*. However, once the thermal blanket is established, adding more $CO_2$ has only a minimal effect on the thermal blanket, and reduced upward IR radiation from the surface does not produce significant warming. This is referred to by Dufresne, et al. [7] as the "saturation paradox".

In the other context, we are concerned with the effect of adding more $CO_2$ to the current atmosphere where the $CO_2$ concentration is already 400+ ppm, and the thermal blanket is already in place, restricting upward IR-radiation. This is labeled the *current greenhouse gas effect*, and it is quite different from the *fundamental greenhouse gas effect*. In the current atmosphere, energy transfer from the Earth to the atmosphere is primarily by evaporation and thermals, and IR-radiant energy transfer is significantly impeded by an almost opaque lower atmosphere. The "thermal blanket" is in place, but it doesn't change much as $CO_2$ is added to the atmosphere. Adding $CO_2$ to the current atmosphere slightly increases the opacity of the lower atmosphere but this is of little consequence. In the upper atmosphere, $CO_2$ is the major means of energy transport by IR radiation. The greatest effect of adding $CO_2$ to the current atmosphere is to extend the upward range of IR-radiant transmission to higher altitudes. The main region where the Earth radiates to space is thereby extended to higher altitudes where it is colder, and the Earth cannot radiate as effectively as it could with less $CO_2$ in the atmosphere. The Earth warms until the region in the upper atmosphere where the Earth radiates to space is warm enough to balance incoming solar energy.

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