igMin RESEARCH A BioMed & Engineering Journal
Focusing on Biology, Medicine and Engineering disciplines
BIOLOGY ISSN 2995-8067
Climate Change Biology

Article Information
Submitted: November 11, 2025
Approved: December 08, 2025
Published: December 09, 2025

How to cite this article: Rapp D. How Increased CO_2 Warms the Earth. IgMin Res. December 09, 2025; 3(12): 454-461. IgMin ID: igmin324; DOI: 10.61927/igmin324; Available at: igmin.link/p324

Research Article

How Increased CO_2 Warms the Earth

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Abstract

It is widely believed that emission of greenhouse gases, particularly CO_2, is warming the world, and the consequences of this are serious. The world is heavily engaged in reducing emissions of CO_2. The global effort to reduce emissions involves investment of very large sums, yet the proper scientific explanation of how CO_2 warms the Earth is not widely understood. The objective of this research is to provide a clear, understandable description and quantitative model of the physics whereby increased CO_2 produces global warming.

The Sun continuously inputs power at 341 W/m^2 to the Earth, and the Earth radiates power to space. The difference between the two determines whether the Earth warms or cools to maintain a power balance. The approach taken here is to estimate the effect of rising CO_2 on the ability of the Earth to radiate power to space.

The methodology involves dividing the Earth's atmosphere into 150 100-m layers and modeling CO_2 irradiance (12-17-micron wavelength band) through these layers. Each layer radiates in the IR according to the Stefan-Boltzmann law at its temperature. As the CO_2 concentration increases, the range of primary emitting layers increases in altitude, where it is on average cooler, reducing outward radiation from the Earth in the 12-17-micron wavelength band. The Earth must warm to compensate.

The forcing in the year 2025 was related to the known temperature increase from the 1800s and thus converted the calculated curve of radiative forcing *vs.* CO_2 concentration to a curve of temperature gain from the 1800s *vs.* CO_2 concentration. This plot is of fundamental importance in predicting future climate change and devising policies for mitigation. It indicates that we are likely to reach a temperature increase from the 1800s of 2.0 °C if CO_2 reaches about 500 ppm, and 3.0 °C if CO_2 reaches about 680 ppm.

Six hypothetical scenarios were created for further CO_2 emissions in the 21st century, and future temperatures for each scenario were estimated. The results span a range from 2.2 °C to 2.9 °C for the temperature increase from the 1800s to the year 2100, depending on the emission scenario.

Background

It is widely believed that emission of greenhouse gases, particularly CO_2, is warming the world, and the consequences of this are serious. The world is heavily engaged in reducing emissions of CO_2 by greater use of non-emitting energy sources, increased energy efficiency, and phasing out high-emitting fuels. The global effort to reduce emissions involves investment of very large sums, yet the proper scientific explanation of how CO_2 warms the Earth is not widely understood. The prominent institutions such as NOAA, NSF, NASA, Smithsonian, … typically describe a "thermal blanket" that obstructs outward propagation of IR radiation from the Earth, and adding CO_2 to the atmosphere thickens the "blanket," inhibiting energy loss from the Earth, causing the Earth to warm. This would be a proper description for a hypothetical Earth with no CO_2 in the atmosphere, and as you add CO_2 to that hypothetical atmosphere, the thermal blanket gets thicker and the Earth warms [1,2]. But having reached the current point where the CO_2 concentration is 425 ppm, the thermal blanket is now so thick that adding more CO_2 to the atmosphere hardly changes it. This led some misguided investigators to conclude that rising CO_2 does not produce warming [3]. The problem is that the physical mechanism by which increased CO_2 warms the Earth changes when the CO_2 concentration is as high as it is today (~ 425 ppm), and a different description and scientific approach is called for.

One of the most important challenges to mankind is understanding how its future use of fossil fuels is likely to affect the future climate, and how that might affect commerce and society. An important part of that bigger picture is relating the increase in global average temperature since the 1800s to the current CO_2 concentration in the atmosphere. Typically, complex climate models are used to estimate the relationship between temperature and CO_2 concentration [4,5]. However, such models are like a black box that is difficult to peer into, to understand the specific physics of how increased CO_2 warms the Earth.

It is important to provide a lucid model that is transparent for the physical mechanism whereby increased CO_2 concentration in the atmosphere produces global warming.

Although previous work pointed the way toward understanding that the actual effect of increased CO_2 is to elevate the altitude at which CO_2 in the atmosphere radiates to space (where it is cooler), no simple, clear, quantitative analysis seems to be available [2,6-10]. The average solar power input to Earth is 341 W/m^2 [11-14]. If the Earth radiates an equal amount of power as IR radiation, it will remain in a steady state. Part of the spectrum of IR radiation emitted by the Earth is the 15-17-micron CO_2 band. To the extent that increased CO_2 reduces radiation in the 15-17-micron CO_2 band from the Earth to space, the Earth will warm to compensate and reestablish a steady state at a higher temperature.

In 2024, I published a paper that explains simply and qualitatively the physical mechanism by which adding CO_2 to the present atmosphere warms the Earth [15]. In that article, I pointed out that the common narrative is that there is a "thermal blanket" that resists outward IR radiation, and adding CO_2 to the atmosphere thickens the blanket, producing warming. I showed that the thermal blanket idea would be appropriate for a hypothetical Earth with no CO_2 in the atmosphere and would describe the effect of initially adding CO_2 in moderate amounts [15]. But when the atmosphere already contains more than 300 ppm CO_2, the thermal blanket is so effective that adding small amounts of CO_2 hardly changes the thermal blanket, and warming derives from a totally different mechanism. The widely disseminated "thermal blanket" narrative does not properly describe the warming effect of rising CO_2 with the CO_2 concentration at present levels. Adding CO_2 to the atmosphere raises the average altitude in the atmosphere where IR is radiated to space, and since it is cooler there on average, the Earth cannot radiate as much power when CO_2 increases, and the Earth warms to reestablish thermal equilibrium. There is great interest in this topic, as evidenced by the fact that my published article was viewed 35,000 times and downloaded 540 times. However, my paper was qualitative and descriptive, and it did not provide quantitative details of the radiant transfer process in the atmosphere.

Recently, I accidentally came across a series of postings on a blog by Dr. Clive Best that provides very important data and understanding that should have been included in my paper, had I known it existed. I thought I had done an adequate search, but because search engines prioritize blog postings very low in their responses to queries, I missed this important work. Not all important science is recorded in the peer-reviewed literature.

This paper is an Addendum to my previous paper, incorporating my attempt to interpret Best's important work. It provides a clear, understandable, quantitative description and calculation of how increased CO_2 warms the Earth – a necessary and critical need for a world so heavily invested in mitigating climate change.

Introduction

The Sun continuously inputs power at 341 W/m^2 to the Earth, and the Earth radiates power to space. The difference between the two determines whether the Earth warms or cools to maintain a power balance. We can estimate the power input from the Sun reasonably well, but estimation of the rate of energy loss is far more difficult.

One approach is to model the upward flow of IR from the Earth's surface through the atmosphere. Although the equations become complex, the model can be understood in simple terms. Evaporation and convection drive power upward in the lower atmosphere. At higher altitudes, water is frozen out, and the density is low enough that energy is transmitted preferentially by IR radiation. There is a continual flow of IR radiation up and down, with a net flux upward. This is due to the fact that the temperature decreases with increasing altitude, and emission is thereby reduced with increasing altitude, while absorption depends on the absorptivity and the intensity of the incident radiation. If you think of the atmosphere as a series of layers, and each higher layer decreases in temperature, then each layer will radiate more power to the layer above it than it receives from the layer above it.

The IR radiation in the 13-17-micron band is particularly important and is controlled by the CO_2 concentration in the atmosphere. Although the Earth radiates energy in other wavelengths, the effect of increasing CO_2 can be estimated by concentrating on the 13-17-micron band.

The appropriate way to consider the effect of increasing CO_2 is to consider the emission of IR radiation from the atmosphere. Here we use the term "IR" as shorthand to mean the IR in the 13-17-micron band where CO_2 absorbs. Carbon dioxide molecules emit and absorb IR radiation to one another in the atmosphere, flooding the atmosphere with IR. As the atmospheric density decreases with increasing altitude, an altitude is reached where the CO_2 concentration is too low to maintain this IR exchange, and this might be thought of as the top of the atmosphere for the IR. More specifically, when the density is low enough that about half of the IR passes through a 100-m thick volume, we can consider that as roughly the IR-effective top of the atmosphere.

Because the density and temperature of the atmosphere decrease with altitude, there is a bias, and more IR is transmitted outward than inward at all altitudes. If one can imagine the atmosphere divided into many horizontal layers, a fraction of the IR from each layer escapes the Earth and contributes to the cooling of the Earth. The higher the altitude of each layer, the greater is the fraction of IR radiation that can escape. IR radiation from the Earth occurs preferentially at higher altitudes. The total radiation emitted by the Earth to space is the sum of contributions from all the layers, each layer emitting according to its local temperature. As more CO_2 is added to the atmosphere, the layers that contribute to outward emission increase in altitude where it is cooler, and since emission of radiation is less efficient at lower temperatures, the Earth is less efficient at radiating to space, and the Earth warms to compensate.

In a previous paper, I outlined this description of how

ISSN 2995-8067 DOI: 10.61927/igmin324

the Earth warms when CO_2 is added to the atmosphere already containing a significant amount of CO_2 [15]. Since then, I discovered the unpublished work of Clive Best that quantitatively models this process, providing much greater detail and new insights into how the Earth warms when CO_2 is added to the atmosphere already containing a significant amount of CO_2. Unfortunately, that analysis is buried in a Blog which is difficult to find and is probably widely ignored by the climate science community. Yet, this analysis is probably the best and most important existing analysis of how adding CO_2 to the atmosphere warms the Earth - a very important work. In this

Clive Best's model of the greenhouse effect

In a series of papers, Clive Best explained, described, and clarified the effect of adding CO_2 to the atmosphere already containing a significant amount of CO_2 (300+ ppm); how it reduces radiant power emitted from the Earth to space, producing global warming [16]. In this paper, I provide my best efforts to interpret Best's important work.

In an early paper, Best described the basic model [16]. Only the 13–17-micron band of CO_2 was considered. The atmosphere is assumed to be dry with no other greenhouse gas present.

It was assumed that the surface of the Earth radiates as a blackbody temperature of 288K. The atmosphere is divided into 150 layers, each 100 m thick. Each layer absorbs photons from any direction according to its local temperature and the density of CO_2 at that level. In the initial model, he started at the bottom and worked his way up. At each level, the transmitted and absorbed IR from below were calculated. The actual net IR flux upwards is the difference between the up-going radiation and the integral of all the higher levels of down-going radiation. Thermal equilibrium is assumed for each level. The IR fluxes up and down were then stored for each level. As Best explained:

"The way to think about it is that radiation from the sun heats the surface (modulated by clouds). The surface then cools by IR radiation (Stefan-Boltzmann). S-B frequencies coinciding with CO_2 and H_2O resonant frequencies are absorbed by greenhouse gases and re-emitted up through the atmosphere to where the atmosphere is thin enough for those photons to escape to space. As a result, the surface loses heat faster through convection of warm surface air upwards to a height where the air is thin enough for all radiation to escape to space. This defines the tropopause where convection stops."

He provided a model for the temperature as a function of altitude (Figure 1) [17].

The net total radiant power emitted by the Earth is a sum of all contributions from the 150 layers of atmosphere, each at its own temperature according to Figure 1. For layers below 10 km, the temperature decreases with increasing altitude. For layers at altitudes between 10 km and 15 km, the temperature is independent of altitude.

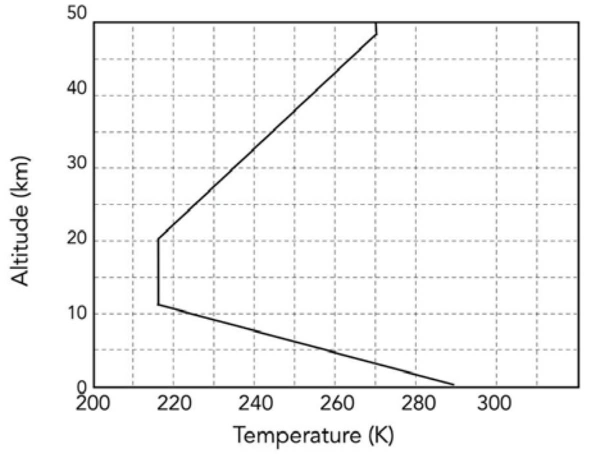

Figure 1: Model for temperature *vs.* altitude in the atmosphere [18].

The key to the calculation is this: Best summed up all the outgoing radiant power from all the layers at CO_2 = 300 ppm. He also did the same for CO_2 = 600 ppm. At 600 ppm, more of the radiant emission takes place in higher layers where more of the layers are cooler, so the net radiant power is less, and the deficit in the Earth's energy balance requires that the surface must shift to warmer temperatures.

In a later publication, Best changed the model, and instead of starting at the Earth's surface, he started at the top layer and worked his way down [18]. Best explained:

"IR radiation originating from space is tracked downwards to Earth to derive for each wavelength the height at which more than half of it gets absorbed within a 100-meter layer. This identifies the height where the atmosphere becomes opaque at a given wavelength. This also coincides with the *effective emission height* for IR radiation to escape from the atmosphere to space. A program was written using a standard atmospheric model to perform a line-by-line calculation for CO_2 with data from the HITRAN spectroscopy database. The result for CO_2 showed that outgoing radiant power from the central peak of the 13-17-micron band originates from high in the stratosphere, where it is comparatively warmer. It is mostly the lines at the edges of the band that lie in the troposphere, where it is cooler. The calculation then reveals how changes in CO_2 concentration affect the emission height and thereby reduce net outgoing radiant power as the CO_2 concentration is increased. This demonstrates how the greenhouse effect on Earth is determined by greenhouse gases in the upper atmosphere and not [via a thermal blanket] at the surface" [18].

Best illustrated the difference between CO_2 = 300 ppm and CO_2 = 600 ppm by plotting the emission height (the altitude where 50% of the entering IR passes through a 100-m layer) *vs.* wavelength within the 13-17-micron CO_2 band *vs.* wavelength. Essentially, all the emission at any wavelength comes from below the emission height. At any wavelength where the emission height for 300 ppm occurs at temperatures warmer

ISSN 2995-8067 DOI: 10.61927/igmin324

than 216 K, the corresponding emission height at 600 ppm will occur at a lower temperature (Figure 2). At CO_2 = 300 ppm, for most wavelengths, the range of effective temperatures is higher than for CO_2 = 600 ppm, so when CO_2 increases from 300 ppm to 600 ppm, the layers that radiate to space are cooler on average, reducing the outflow of radiant power at 600 ppm compared to 300 ppm (Figure 3). The temperatures shown in Figure 3 allow calculation of the radiant power emitted at the emission height for each CO_2 concentration.

This model explains the mechanism of how increasing the CO_2 concentration reduces outgoing radiant power from the present atmosphere, thereby creating an energy imbalance, causing the Earth to warm.

Now that Best had the atmosphere divided into 150 100-m layers with an estimated temperature for each layer, he applied the Planck radiation law to determine the radiant power emitted at each wavelength in the 15-17-micron wavelength band at each CO_2 concentration. Summing up from all the layers, he estimated the total radiant emission in the 15-17-micron wavelength band at each concentration of CO_2. Choosing the radiant emission at 100 ppm as a baseline, we plot the radiant forcing defined as radiant emission at any ppm minus radiant emission at 100 ppm in Figure 4. Clive Best also compared his result to a published paper that utilized a complex atmospheric model to estimate the radiative forcing and found good agreement [7].

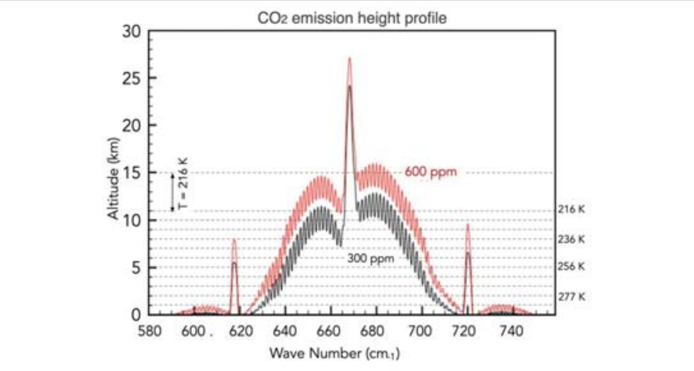

Figure 2: CO_2 emission height profiles for CO_2 = 300 ppm and for CO_2 = 600 ppm, smoothed with a resolution of 20 lines [18].

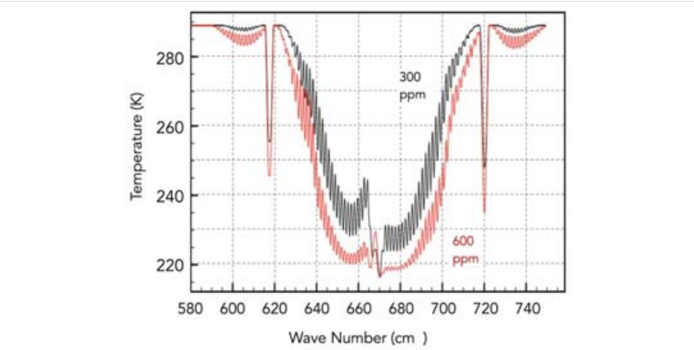

Figure 3: The temperature at CO_2 emission heights for CO_2 = 300 ppm and for CO_2 = 600 ppm [18].

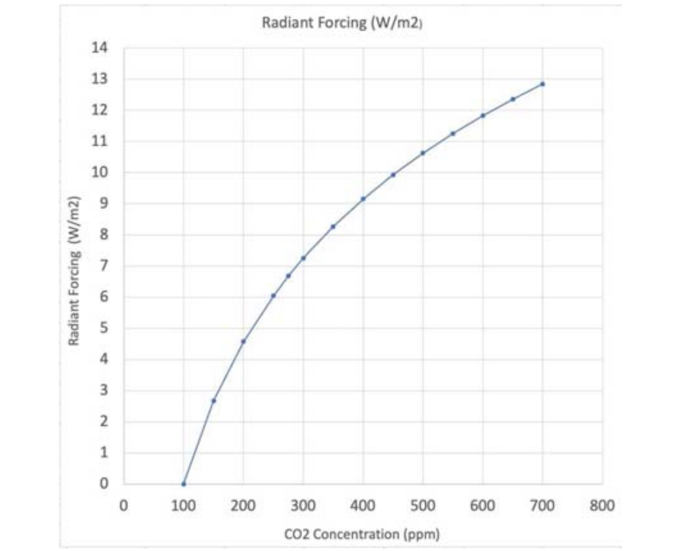

Figure 4: Radiant forcing = radiant emission at any ppm minus radiant emission at 100 ppm. This curve is well fitted by the equation RF = 6.6 LN (ppm/100) [19].

While Best used 100 ppm as a baseline, it is more convenient to use 275 ppm as a baseline because that corresponds to the mid-1800s. If we select the outgoing radiant emission at 275 ppm (corresponding to the mid-1800s) as a baseline, then subtracting the total radiant emission at any CO_2 concentration from the total radiant emission at 275 ppm yields the deficit in total radiant emission at any CO_2 concentration compared to that in the 1800s. Best's model produces the plot shown in Figure 5. Since Best's model maintains the Earth's surface temperature at 288 K, the difference between radiant emission (RE) at 275 ppm and any higher ppm represents what is commonly called the "radiant forcing" that would drive the Earth's temperature higher. The increase in radiant forcing per unit increase in CO_2 concentration decreases at increasing CO_2 concentrations.

According to this model, the radiant forcing already reached about 3 W/m^2 in 2025, which is about half of the radiant forcing at 700 ppm.

In review, Best's model involves these steps:

1. Divide the atmosphere into 150 100-m thick layers, each layer at the temperature shown in Figure 1 for its altitude.
2. For any particular concentration of CO_2 (ppm), calculate the outgoing IR radiant emission from each layer.
3. Sum over all layers to obtain the outgoing IR radiant emission from the atmosphere at any particular concentration of CO_2 (ppm).
4. Take the difference between the outgoing IR radiant emission from the atmosphere at 275 ppm (characteristic of the 1800s) and any other CO_2 concentration (ppm) to get the net radiant forcing at that ppm.

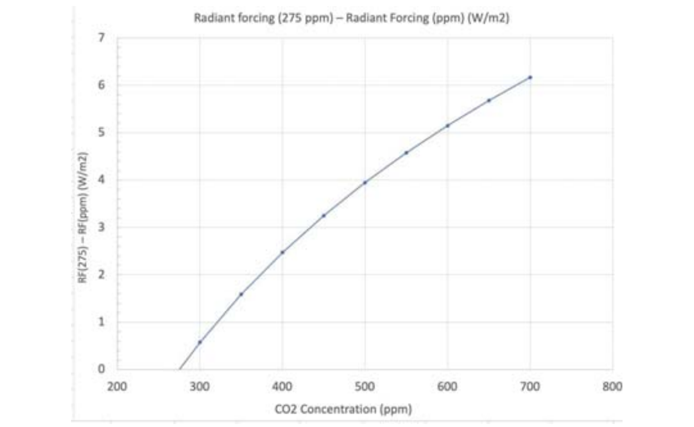

Figure 5: The difference between radiant emission in the 15–17–micron band between CO_2 at 275 ppm and any other ppm – otherwise known as the "radiant forcing" at any ppm. This curve is well fitted by the equation RF = 6.6 LN(ppm/100) – 6.6 LN(275/100).

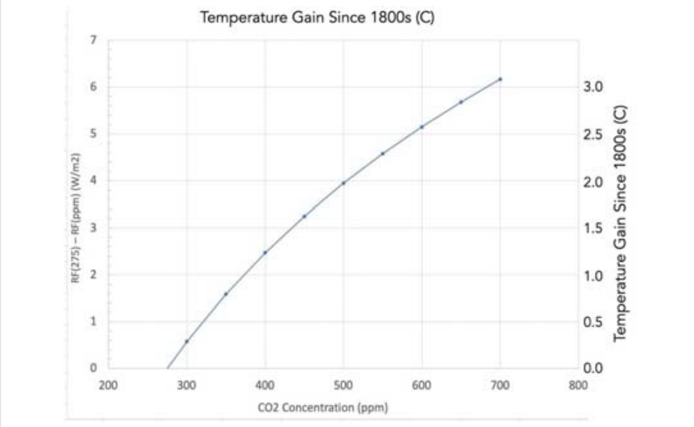

Figure 6: Estimate of temperature gain since the 1800s *vs.* ppm CO_2. Note that the temperature gain at 425 ppm was 1.5 °C in the year 2025. This curve is well fitted by the equation: ΔT = 3.43 LN(ppm/100) – 3.43 LN(275/100) = 3.43 LN(ppm/275).

Best used the radiative forcing data to estimate how much the Earth would warm for any increase in CO_2 concentration [19]. That required assumptions about clouds, emissivity, and blackbody radiation. Here, we take a more pragmatic approach. In 2025, the CO_2 concentration was about 425 ppm, where the radiative forcing was about 2.9 W/m^2, and the temperature gain from the 1800s was about 1.5 °C. We might therefore assume that each W/m^2 of radiant forcing produces a temperature rise from the 1800s of (1.5/2.9) = 0.52 °C. We can then convert Figure 5 to a temperature plot as shown in Figure 6.

In a previous paper, Rapp (2024) estimated the temperature gain since the 1800s *vs.* ppm CO_2, but he assumed that the relation between temperature gain and CO_2 ppm was linear, whereas here we find it is logarithmic [20] His estimates for temperature gain at high ppm CO_2 were therefore too high. We compare estimates for temperature gain *vs.* ppm CO_2 from Rapp (2024), the present calculation, and Best's estimate in Figure 7. The present model has the temperature gain at 1.5 °C for 425 ppm and predicts a temperature gain of 3.0 °C at 680 ppm.

The model can be tested for the recent past by downloading CO_2 data and estimated global average temperature data from NOAA, and thereby relating the two since 1980. The result is shown in Figure 8. The model runs consistently high compared to the data. However, it is well known that in this period, power plants emitted copious amounts of aerosols that had a cooling effect to slightly reduce global warming from CO_2 [21]. Since then, aerosol emissions have been greatly reduced, and the curve of temperature gain *vs.* CO_2 has increased.

Consequences for the 21st century

The relationship between temperature growth since the 1800s to CO_2 concentration at any date in the 21st century is given by:

T(ppm) – T(275 ppm) = 3.43 LN(ppm/275).

We can use this relationship to estimate the growth in temperatures since the 1800s for any arbitrary scenario for CO_2 emissions in the 21st century. Our model will be based on annual emissions of CO_2, but we have a relationship between temperature and ppm of CO_2. Therefore, we need an estimate of the increase in ppm CO_2 for each Gt of CO_2 emitted. This was provided by Rapp (2024) [20].

The Earth's atmosphere has an estimated mass of 5.15 x 10^6 Gt. The molecular weight of the atmosphere is about MW ~ 28.96. The atmosphere includes about (5.15 x 10^6)/28.96 = 1.78 x 10^5 moles and 1 Gt of CO_2 is 1/44 = 0.0227 Moles. If 1 Gt CO_2 remained in the atmosphere, the molar ratio of CO_2 would be

(0.0227)/(1.78 x 10^5)= 1.30 x 10^{-7} = 0.130 ppm

Thus, emission of 1 Gt CO_2 would increase the concentration of CO_2 in the atmosphere by 0.130 ppm – if it all remained in the atmosphere. Here, we assume that 50% of the emitted CO_2 remains in the atmosphere, so that each Gt CO_2 emitted by the world increases the CO_2 concentration by 0.065 ppm. Thus, it would take the emission of 15.4 Gt CO_2 to raise the concentration by 1 ppm.

We consider several conceptual future scenarios for the emission of CO_2 as shown in Figure 9.

By summing up each year's emissions from Figure 9, the cumulative emissions after 2025 can be determined as shown in Figure 10.

We previously derived the increase in CO_2 ppm for any amount of CO_2 emissions. That allows us to convert the cumulative emissions in Figure 10 to a plot of CO_2 concentration as shown in Figure 11.

Using the relationship between CO_2 ppm and temperature gain since the 1800s shown in Figure 8, the data in Figure 11 is converted to a plot of temperature gain *vs.* year for each scenario as shown in Figure 12. Figure 12 provides government and institutional planners with reliable estimates of future temperature gain for various reasonable scenarios of future emissions.

ISSN 2995-8067 DOI: 10.61927/igmin324

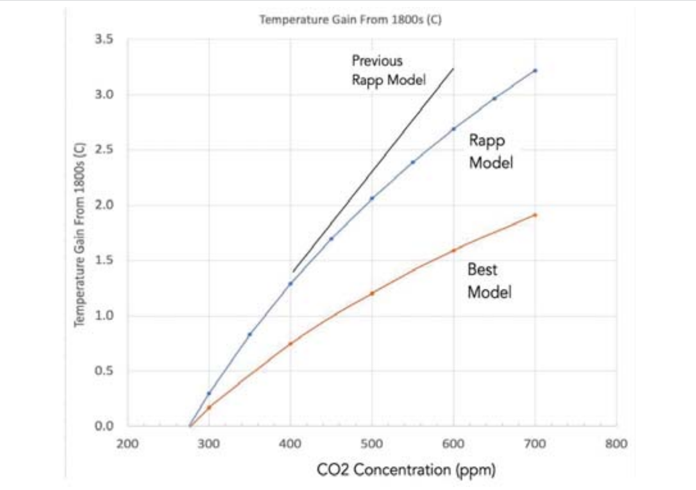

Figure 7: Comparison of present calculation (Rapp Model), Best's calculation [19], and Rapp's previous model [20].

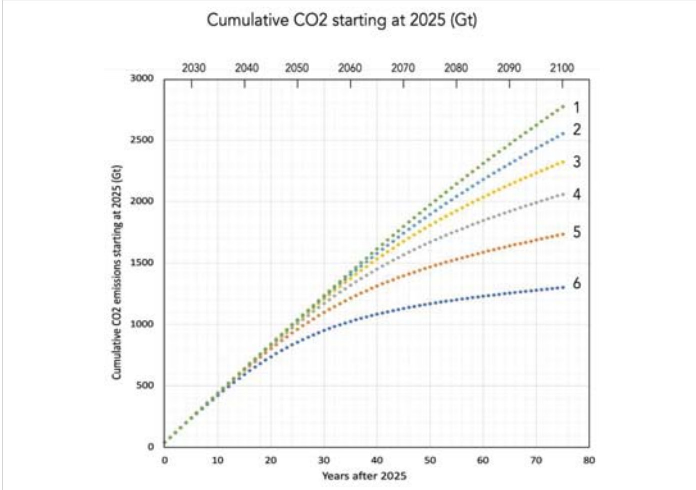

Figure 10: Modeled cumulative CO_2 emissions for the period 2025 to 2100 according to six scenarios.

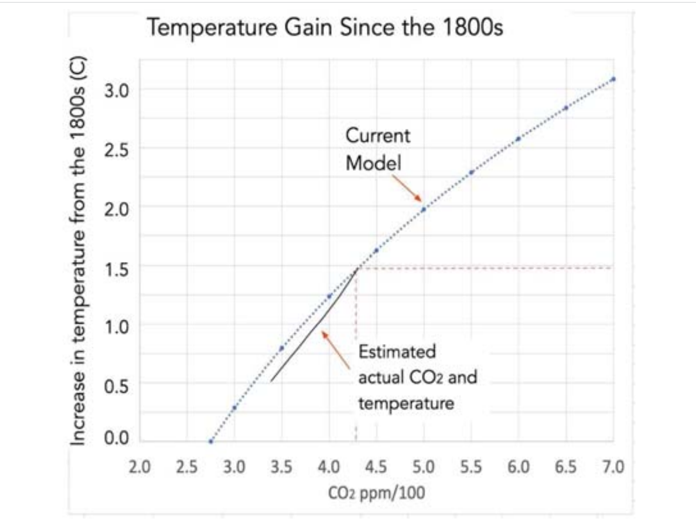

Figure 8: Comparison of the model to the data for temperature *vs.* CO_2 from 1980 to 2025.

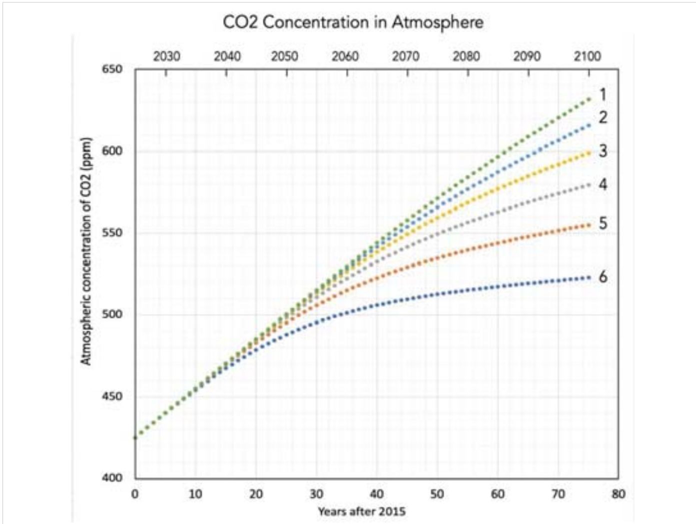

Figure 11: Modeled CO_2 concentration (ppm) for the period 2025 to 2100 according to six scenarios.

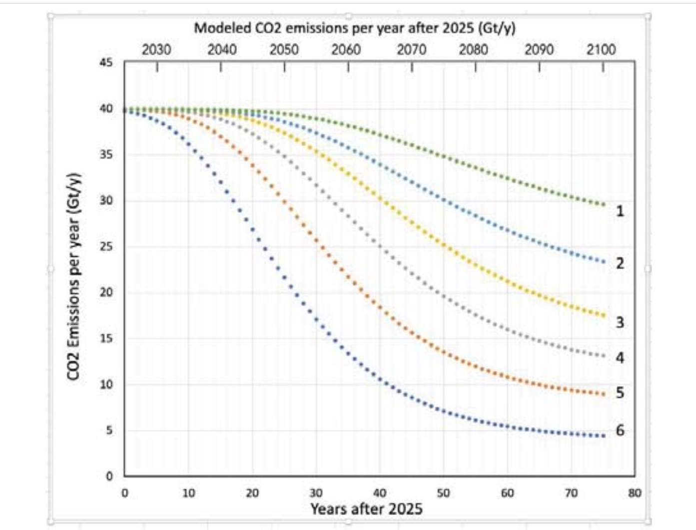

Figure 9: Modeled CO_2 emissions for the period 2025 to 2100 according to six scenarios.

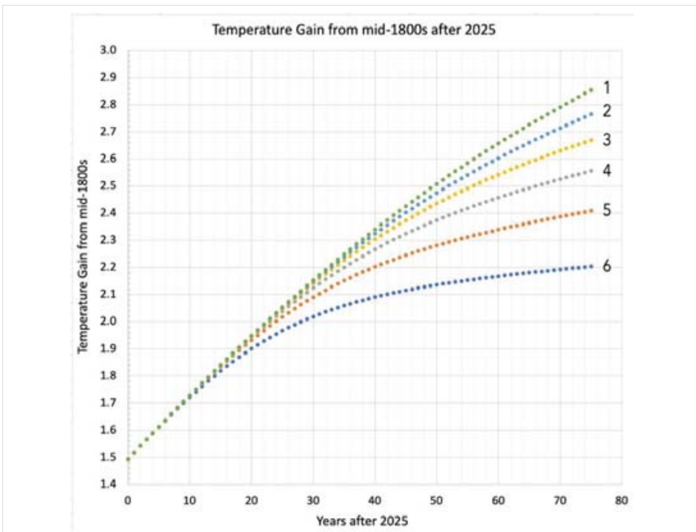

Figure 12: Modeled temperature gain from the 1800s for the period 2025 to 2100 according to six scenarios.

Discussion

In a previous paper, I pragmatically estimated global average temperatures in the 21st century for a set of hypothetical emission scenarios in the remainder of the century after 2015 [8]. In that paper, I assumed that the temperature rise was proportional to the CO_2 concentration, and I used pragmatic empirical data. The physics of warming by CO2 was not considered. Since then, I discovered the analysis of the physics by which increased CO_2 produces global warming that Clive Best posted on a Blog, and he showed that the warming depends logarithmically on CO_2 concentration, which indicates that my previous paper overestimated future warming because it used a linear relationship.

This paper provides a detailed quantitative analysis of the physics involved in the warming of the Earth by increased CO_2. The atmosphere is divided into 150 100-meter layers, and CO_2 irradiance (12–17-micron wavelength band) through these layers is modeled. Each layer radiates in the IR according to the Stefan-Boltzmann law at its temperature. As the CO_2 concentration increases, the range of primary emitting layers increases in altitude, where it is on average cooler, reducing outward radiation from the Earth in the 12–17-micron wavelength band. The Earth must warm to compensate. The radiative forcing is the net loss in radiative power due to increased CO_2. The radiative forcing was calculated *vs.* CO_2 concentration – a very basic and important relationship in climate change analysis. Because Clive Best's analysis is posted on a Blog where it is not noticed by search engines, it is not widely cited in the literature. In the present document, I am endeavoring to make his important work more widely known.

I related the forcing in the year 2025 to the known temperature increase from the 1800s and thus converted Best's curve of radiative forcing *vs.* CO_2 concentration to a curve of temperature gain from the 1800s *vs.* CO_2 concentration (Figure 6). This plot is of fundamental importance in predicting future climate change and devising policies for mitigation. It indicates that we are likely to reach a temperature increase from the 1800s of 2.0 °C if CO_2 reaches about 500 ppm, and 3.0 °C if CO_2 reaches about 680 ppm.

I then proceeded to create six hypothetical scenarios for further CO_2 emissions in the 21st century with a start date of 2025, using the logarithmic dependence of temperature on CO_2 concentration, rather than the linear approximation used previously. The results span a range from 2.2 °C to 2.9 °C for the temperature increase from the 1800s to the year 2100, depending on the emission scenario.

The challenge for the world in the 21st century will be to provide the world with energy to support a robust global economy, while at the same time reducing CO_2 emissions. There will be conflict between these two goals, and the actual future scenario will reflect the economic, technological, political, and social forces. The IPCC developed similar scenarios, but their scenarios are derived from specific allocations of various energy sources in the future [4]. Based on current trends, Scenario 4 seems to be a reasonable guess.

Conclusion

The global effort to reduce CO_2 emissions involves investment of very large sums, yet the proper scientific explanation of how CO_2 warms the Earth is not widely understood. The primary objective of this research is to provide a clear, understandable description and quantitative model of the physics whereby increased CO_2 produces global warming. A secondary objective is to provide an estimate of global temperatures in the 21st century for a range of potential future emission scenarios, which provides valuable information for planning future energy systems and government regulations.

This paper provides a clear, understandable description of the physics whereby increased CO_2 produces global warming. It also provides insight into expected temperature gain in the 21st century for a range of potential future emission scenarios.

This model is not a full climate model. It does not take into account the main forces that act in the climate system. It focuses on one aspect of the climate that is likely to be a major factor, the effect of increasing CO_2, reducing the ability of the Earth to radiate power to space. To the extent that this is a dominant factor in climate change from the 1800s to 2100, this can be taken as a guide for the likely temperature in the remainder of the 21st century.

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How to cite this article: Rapp D. How Increased CO_2 Warms the Earth. IgMin Res. December 09, 2025; 3(12): 454-461. IgMin ID: igmin324; DOI: 10.61927/igmin324; Available at: igmin.link/p324

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