Response to R. I. Holmes on the Ideal Gas Law, Thermal Enhancement, and the Greenhouse Effect

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Abstract

This work responds to Holmes (2017, 2018; DOI: 10.11648/j.earth.20170606.18, DOI: 10.11648/j.earth.20180703.13), which assert that the Ideal Gas Law (IGL) predicts planetary surface temperatures and shows that increases in atmospheric CO_2 can have only minimal impact on temperatures; also asserting that the greenhouse effect does not produce significant warming, and that surface temperatures are enhanced by convection and "auto-compression." It was argued that Holmes's use of the IGL to calculate planetary temperatures is more accurate characterized as a process for indirectly measuring temperature, with little in the way of predictive power. The claimed calculation of a small climate sensitivity to doubling of CO_2 was shown to rely on an unjustified assumption, amounting to circular reasoning. Holmes's observation that the thermal gradient in the troposphere is largely due to convection is well-known and uncontroversial. It was clarified that the existence of a thermal gradient due to convection in no way explains the "residual" temperature difference between the surface temperature and the planetary effective temperature. A given lapse rate can correspond to any surface temperature, and any "residual"; the lapse rate offers no information about the surface temperature or the residual temperature difference. Holmes offers no testable hypothesis, no evidence, and no logical argument, to support his premise regarding the cause of the "residual"; his suggestions that the residual is due to "gravitationally-induced adiabatic auto-compression, powered by convection" were determined to be vague unsupported speculation. Each of Holmes's arguments against the greenhouse effect was found to be based in a misunderstanding of the greenhouse effect. The greenhouse effect was defined and quantified. It was found that these papers by Holmes failed to justify any of their major claims.

1 Introduction

In 2017, Robert Ian Holmes published "Molar Mass Version of the Ideal Gas Law Points to a Very Low Climate Sensitivity" [1]. In 2018, he followed this up with "Thermal Enhancement on Planetary Bodies and the Relevance of the Molar Mass Version of the Ideal Gas Law to the Null Hypothesis of Climate Change" [2]. These papers argue that (a) the molar mass version of the Ideal Gas Law (IGL) predicts planetary temperatures, (b) there is unlikely to to be significant warming from the greenhouse effect at pressures above 10 kPa, and (c) differences between the measured near-surface air temperature and planetary effective temperature may be explained in terms of gravitationally-induced adiabatic auto-compression, powered by convection.

Holmes's papers have become influential among some of those who are skeptical of anthropogenic climate change. Thus, their conclusions merit examination. The conclusions of Holmes [1, 2] are thoroughly misleading, as this work will show.

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Holmes [2] repeats and extends the arguments of Holmes [1], so I will focus on the later paper, except where the prior paper says something in a way that seems clearer.

In addition to offering a core argument about the IGL, Holmes [2] offers a variety of arguments regarding climate change. Most are widely-made arguments which seem to not be specifically relevant to the core of Holmes's work. So, I will address in this paper only arguments related to the IGL, thermal gradients, and the greenhouse effect.

2 Ideal Gas Law

2.1 IGL: Non-Significance of Verification on Planets

Holmes [2] offers the Ideal Gas Law (IGL) in what he identifies as its "Molar Mass Version":

$$T = \frac{P}{R \times (\rho / M)} \tag{1}$$

where T is temperature, P is pressure, R is the gas constant, M is molar mass, and ρ is mass-density [2, Formula 5].

Holmes makes a point of applying the Ideal Gas Law (IGL) to calculating the near-surface temperature on eight planetary bodies, based on estimates of atmospheric pressure and density. This is compared to the measured surface temperature, and the errors are found to be generally small.

The IGL is well-established and known. It is known to be universally valid, aside from errors which are corrected in "real gas" forms of the gas law [3]. No planetary scientist would ever release data which was inconsistent with the gas law; they would find their error and fix it before releasing the data.

So, *Holmes's verification that the gas law applies on different planets is pointless and of no significance*.

Out of the seven bodies other than Earth considered by Holmes, only four have ever had instruments enter their atmospheres (Venus, Mars, Jupiter, Titan). Atmospheric probes typically have instruments that measure temperature and pressure. However, I have been unable to identify any atmospheric probe which carried an instrument for measuring atmospheric density.

In the case of the Hyugens probe that entered the atmosphere of Titan:

> "Density values relevant to the lower atmosphere, below 160 km, have been inferred from HASI direct measurements of pressure and temperature with the assumption of hydrostatic equilibrium and real gas law." [4]

In other words, in the case of Titan, the *density* value Holmes uses to calculate temperature was itself *an inferred value calculated by starting with temperature data and applying the gas law*.[1]

While I have not traced the source of all the density values referenced by Holmes, it seems likely that most, if not all, density values were calculated by applying the Ideal Gas Law, or a Real Gas Law, in combination with other data, to infer the reported density value.

To the extent that this is the case, Holmes's finding that the IGL and pressure and density data may be used to calculate temperature amounts to circular reasoning, or at least, something that would inevitably be true given the origin of the data.

Suppose it turns out that the referenced density values were not inferred using the IGL. Even so, finding that pressure, density, and temperature are related via the IGL, even on different planets, is in no way surprising.

The IGL describes the behavior of gases, subject to modifications for real gases. That finding is not new nor is it in dispute.

2.2 IGL: Indirect Measurement

Suppose someone told you

> "Take this old-fashioned mercury thermometer to the surface of a planet, tell me the height of the mercury, and I will calculate the temperature."

Few people would be impressed by the person's ability to calculate temperature. Nor would anyone regard it as a means of "predicting" temperature. The person is simply offering a procedure for measuring temperature.

Yet, the process of calculating planetary temperature based on pressure, density, and the IGL is not so different.

Atmospheric pressure is simply determined by the weight of the atmosphere above a given location. Given that pressure and atmospheric composition are known, it follows that *temperature and density are two sides of the same coin:* if you know one, then you know the other.

Most people would not be impressed by someone who said

> "I can predict coin tosses: toss a coin, tell me which side is up, and I can consistently use that information to 'predict' which side is down."

Holmes is making an analogous argument.

Holmes [2] argues that information from "parameters previously thought to be essential for the calculation of atmospheric temperatures, such as; solar insolation, albedo, greenhouse gas content, ocean circulation and cloud cover among many others" is "already automatically 'baked-in' to the three gas parameters... the atmospheric pressure, the atmospheric density and the mean molar mass."

That is true but misleading. It is true in the same sense that which side of a coin is facing up contains "baked-in" information about the velocity and angular velocity of the tossed coin as it was launched, air resistance, the dynamics of the coin landing, and so on.

The misleading aspect is the suggestion that the procedure makes *predictions*. It doesn't.

Knowing which side faces up replaces the hard process of making a prediction with the simple process of

[1] Holmes [1] acknowledges that the "temperature of the surface of Titan...... was probably used as an input to find the surface density... This could be seen as a circular argument."

checking the outcome. Once the outcome of a coin toss has already been decided, 'measuring' which side of a tossed coin is facing up can be used as an indirect way of 'measuring' which side is facing down.

Checking an outcome after it has happened is simple. But, it is not a method for "predicting" anything.

The information of which coin side faces up, or the values of the gas parameters, encodes information about *what has already happened*. It is *not* information that supports a prediction of *what will happen*.

The recipe "Measure the atmospheric density and pressure and I will calculate the temperature" is simply an indirect way of *measuring* the temperature, or checking the outcome *after* it has happened.

2.3 IGL: Different Atmospheric Compositions

Holmes [2] marvels that his formula 5 (a form of the IGL) can "accurately predict the average atmospheric temperature of eight such widely differing planetary atmospheres."

All reason to marvel at the result disappears if one acknowledges that measuring density and then applying formula 5 is simply a recipe for indirectly measuring planetary temperature.

Imagine measuring the pressure, density, and temperature inside

- an oven full of nitrogen (molar mass 28 g/mol) at 200°C;
- an oven full of argon (40 g/mol) at 200°C;
- a freezer with nitrogen at -20°C;
- a freezer with argon at -20°C; and
- the flames of a gas burner.

In every one of these instances, applying the IGL to values for pressure and density is likely to provide a good estimate of temperature. Yet, in *none* of these cases could the IGL reasonably be said to be offering a "prediction" of the temperature. In each case, the temperature is determined by factors that have nothing to do with anything within the realm of what the IGL addresses.

Other factors determine the temperature. Then density is in turn determined by the temperature.

The IGL simply tells us how density and temperature (and pressure) will be related, *after* the temperature has been determined.

After other factors have established the temperature and density, then one can measure the density and apply the IGL, as a way to indirectly measure the temperature.[2]

The IGL, as applied by Holmes, is part of *a recipe for measurement, not a recipe for prediction.*

2.4 IGL: Measurements vs. Explanations and Predictions

Holmes [2] asserts that his formula (5) (the IGL) "predicts" planetary temperature. I have seen others claim Holmes [1, 2] demonstrated that the IGL "explains" planetary temperature.

For a theory to "predict" or "explain" something, it ought to be able to tell you, *prior to something happening*, what will happen. And, the greater the range of situations in which an theory allows you to anticipate what will happen, the greater the "explanatory power" of that theory.

The IGL as a means of predicting planetary temperature does not pass this test. It is only useful for making such predictions if one also has *a separate theory for predicting the atmospheric density.*

Let us consider trying to predict the final steady-state surface temperature of planets in some hypothetical scenarios:

1. A planet the size and mass of Earth has surface rocks similar to those on the Moon, no oceans or water, and an *initially frozen pure-nitrogen atmosphere*[3] with an area density of 10,000 kg/m². The planet is placed into a circular orbit *1.1 astronomical units* away from the Sun. After the atmosphere warms up and the situation fully stabilizes, what will be the planetary surface temperature?
2. Similar to scenario #1, except the planetary surface is covered with a coating that *reflects 99.9 percent* of sunlight, and has an *emissivity of 0.9*.
3. Similar to scenario #1, except the planetary surface is covered with a coating that *absorbs 99.9 percent* of sunlight, and has a low *emissivity of 0.1*.
4. Similar to any of scenarios #1-3, except that there is *no atmosphere*.

It is well-known that objects left out in the hot Sun will reach different temperatures, depending on how dark or light they are, i.e., depending on their absorptivities. A black object will reach a higher temperature than a white one.

[2] Yet, why one wouldn't simply measure the temperature *directly* is a mystery, given that temperature is typically easier to measure than density.

[3] Note that nitrogen gas is transparent to both sunlight and thermal radiation.

It is equally true, if less well-known, that objects left in the Sun will reach different temperatures depending on their emissivities.[4]

It should be obvious that the planetary temperature is likely to be different in these different scenarios. Indeed, in the no-atmosphere version of the scenarios, the warmest scenario would be expected to have a surface temperature 423 K hotter than in the coolest no-atmosphere scenario. If you think that having an atmosphere would eliminate the temperature differences between scenarios, that would be an extraordinary claim.

It should also be clear that *the IGL by itself can offer no predictions whatsoever about the final temperatures in these situations*. The IGL is only useful after one has measured the density (after the fact) or after one has predicted the density (using some entirely different theory).

In contrast, the techniques of mainstream climate science are perfectly capable of predicting a final steady-state temperature in each of scenarios.

The IGL describes a valid relationship. But, the IGL has very little explanatory or predictive power by itself.

The IGL can not reasonably be said to "explain" or "predict" planetary temperature.

2.5 IGL: Effect of Doubling Carbon Dioxide

Section 2.9 of Holmes [2] purports to calculate the warming effect of doubling the concentration of CO_2 in the atmosphere from 0.04% to 0.08%.

Holmes estimates that this should increase pressure by 0.04% and molar mass by 0.05%, with molar mass being increased from 28.97 to 28.984. My calculations in Appendix B show that both of these estimates are *wrong*. However, in the end, neither of these values matter because of what comes next.

Holmes also estimates that density would increase by 0.05%. Any other density change is regarded as "anomalous." Yet, *this estimate of the change in density is completely unmotivated, with no justification whatsoever.*

Density is a consequence of temperature.

So, the assumption about density change implicitly assumes a particular temperature change. The alleged "calculation" of temperature change is simply an unjustified assumption about how much temperature change there will be.

There is no underlying physics which supports the assumption Holmes makes about density.

[4] Reflectivity/absorptivity and emissivity affect roof temperatures, thereby impacting heating and cooling costs [5].

Thus, *the calculated small temperature change from doubling CO_2 is an assumed result*, with no significance or justification whatsoever.

Beyond the errors identified above, there are additional suggestions that Holmes lacks a full command of the physics involved:

- Holmes considers the possibility of pressure changing in connection with a temperature change. Yet, in an atmosphere, pressure is determined by the mass of the atmosphere overhead. At a given location within the atmosphere, changing the air temperature cannot change its pressure.[5] If the atmospheric composition does not change other than by CO_2 being added, then neither the mean global surface pressure, nor the molar mass of air, can change by any amount other than what was calculated in Appendix B. As a result, aside from any initial changes, it must be temperature and density that vary together, with *any temperature increase corresponding to a decrease in density.*
- Holmes expresses puzzlement at how density could possibly decrease when a gas with a higher molar mass is being added. Yet, *this is no more mysterious than any instance in which air warms and its density decreases, despite the molar mass not having changed at all.*

The molar density of a gas (moles/m^3) at a given pressure is determined by its temperature, i.e., its energy content. To determine the temperature of a gas, one needs to find out about its energy content—not focus on the molar mass of constituent gases.

As air warms it becomes less dense. There is no great mystery involved.

Climate science asserts that increasing atmospheric CO_2 reduces energy loss to space, causing more energy from sunlight to accumulate on Earth's surface, in the oceans, and in the atmosphere. This energy accumulation raises temperatures, leading to correspondingly less dense air. This narrative is consistent with the IGL. It is the increased energy content that changes the density of the air; the molar masses of the gases involved are largely irrelevant.

Holmes's concerns about how adding CO_2 could possibly correspond to an increase in temperature, despite the minimal change in air's molar mass, are as

[5] The rules are different on Mars, where some of the mass of the atmosphere spends part of the year condensed as dry ice on the surface. Actually, this is an issue on Earth as well, insofar as increasing humidity adds mass to the atmosphere. However, it is simplest to first analyze dry air, as Holmes seemed to be implicitly doing, before adding such complications.

misguided as questioning how the height of the mercury in a mercury thermometer could possibly change, given that the mass of the mercury in the device has not changed.

Holmes claims the IGL "predicts" the warming effect of doubling atmospheric CO_2 to be small. This claim is completely without merit. All that was demonstrated is that *if one implicitly assumes the temperature change to be small, then a small temperature change is what will be calculated;* the claim relies entirely on circular reasoning.

2.6 IGL: Molar-Mass Version as a Source of Confusion

Holmes focuses on what he refers to as the "Molar Mass Version" of the IGL (my equation (1), his Formula 5). Yet, he could have used a different version of the IGL, such as the following equation which is commonly used in statistical mechanics:

$$T = \frac{P}{n\,k_B} \tag{2}$$

where T is temperature, P is pressure, k_B is Boltzmann's constant, and n is the *number density* of particles expressed in molecules/m^3; or he could have used:

$$T = \frac{P}{\rho_m\,R} \tag{3}$$

where ρ_m is the *molar density* or number density expressed in moles/m^3 [6, 7].

All forms of the IGL are equivalent. If equation (2) or (3) had been used, the calculations Holmes did for different planets would have yielded exactly the same results.

In the form of the IGL that Holmes prefers, equation (1), there are two quantities (ρ and M) that depend on mass. This creates a false impression that the mass of different chemical species is significant to the IGL. However, this apparent significance is only an artifact of the variables used to express the IGL.

Equations (2) and (3) eliminate all dependency on mass. This demonstrates that *the molar mass of different chemical species makes no inherent difference to the IGL.*

If Holmes had used equation (2) or (3) to express the IGL, then it might have been clearer that the IGL has nothing to say about the thermal implications of adding different types of molecules to the atmosphere.

3 Thermal Gradients

3.1 TG: Convection and auto-compression

Holmes [2] asserts that

> "planetary bodies which have thick atmospheres, naturally set up a rising thermal gradient in that part of the atmosphere which is higher than a pressure of 10kPa, until that bodies' surface is reached"

He attributes this thermal gradient (or "lapse rate") to "convection and adiabatic auto-compression."

The above conclusion is uncontroversial and is consistent with long-accepted understandings within atmospheric and climate science.[6]

Given that this information has long been well-known to all climate scientists, it seems strange that Holmes imagines that another well-established concept in climate science, the greenhouse effect, is somehow inconsistent with this information. (It isn't.)

3.2 TG: Maxwell and Arrhenius

Holmes [2] quotes James Maxwell:

> "In the convective equilibrium of temperature, the absolute temperature is proportional to the pressure [raised to the power $\frac{\gamma-1}{\gamma}$, or 0.233]."[7]

I have included in brackets the portion of the statement that was omitted by Holmes [9, p. 301].

The statement by Maxwell implies:

$$T(P) = T_s \left(\frac{P}{P_s}\right)^{\frac{\gamma-1}{\gamma}} \tag{4}$$

where $T(P)$ is the temperature at pressure P; and T_s and P_s are the surface temperature and pressure, respectively.

It is not certain why Holmes included the quote from Maxwell. However, it is easy to suspect that Holmes hoped that people would take the quote to mean that

[6] The specific figure 10 kPa is, however, questionable. The pressure at Earth's tropopause varies between 7-40 kPa [8].

[7] The parameter $\gamma = C_p/C_v$ is a ratio of heat capacities. Maxwell indicates (p. 299) $\gamma = 1.408$ for most gases, which corresponds to $(\gamma-1)/\gamma = 0.260$, which in turn corresponds to a lapse rate $\Gamma_d = 9.8$ K/km. The value $(\gamma-1)/\gamma = 0.233$ supplied by Maxwell corresponds to $\gamma = 1.30$ and $\Gamma = 7.9$ K/km; it is not clear where this value came from. If not an error, perhaps it reflects an early attempt to account for the environmental lapse rate.

"air temperature is simply caused by pressure"—which it does *not* mean.

Maxwell was describing how temperature changes with pressure, in accordance with the parameter γ. However, the surface temperature is set by the parameter T_s, which is completely independent of γ. A given value of γ could correspond to any surface temperature at all, as is shown in Figure 1.

Maxwell said *nothing* about how T_s is determined. Maxwell certainly did not say that the value of T_s has anything to do with pressure. (It doesn't.)

It may be shown [10, 11] that equation (4) corresponds to temperature expressed in terms of altitude, z, being given by

$$T(z) = T_s - \Gamma_d \cdot z \tag{5}$$

where Γ_d is the *dry adiabatic lapse rate*

$$\Gamma_d = \frac{g}{C_p} \tag{6}$$

and where g is the gravitational constant; and C_p is the heat capacity of dry air at constant pressure.

In the real world, air is often not dry, and so temperature is instead given by

$$T(z) = T_s - \Gamma \cdot z \tag{7}$$

where Γ is the environmental lapse rate, with a typical value of $\Gamma \approx 6.5$ K/km.

In equation (5), the lapse rate is determined by the properties of air per equation (6); but the surface temperature T_s is left as a free parameter which could take on any value. Thus, *Maxwell's work does not tell us what the surface temperature will be*.

Figure 2 illustrates that, for a given lapse rate, Γ, the surface temperature, T_s, could have any value.

Holmes writes:

> "Maxwell's work shows that temperatures in the lower troposphere of Earth are primarily determined by convection and the atmospheric mass/pressure/gravity relationship. Arrhenius's later work completely ignored this and determined that temperatures in the lower troposphere of Earth are caused by the radiative effects of greenhouse gases."

Holmes is *mistaken in thinking that the work of Maxwell and Arrhenius was in conflict*.

Maxwell's work determined the value of the lapse rate, Γ_d (in dry air, assuming convective equilibrium).

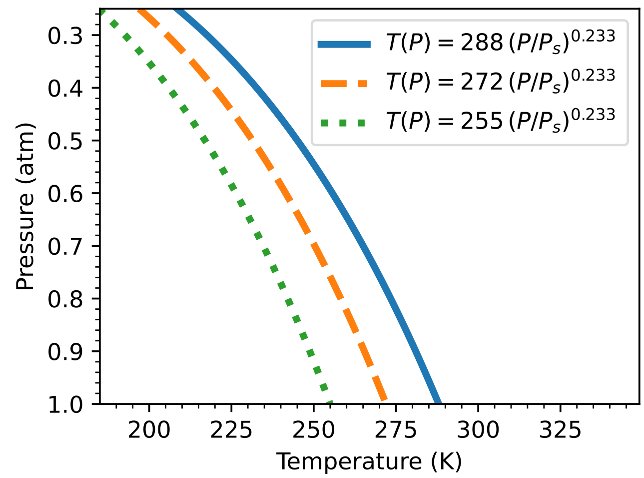

Figure 1: *Maxwell's relationship for how temperature varies with pressure. A given pressure lapse exponent can be associated with any surface temperature. Sample temperature profiles are shown for 3 different surface temperatures, each with the same pressure lapse exponent.*

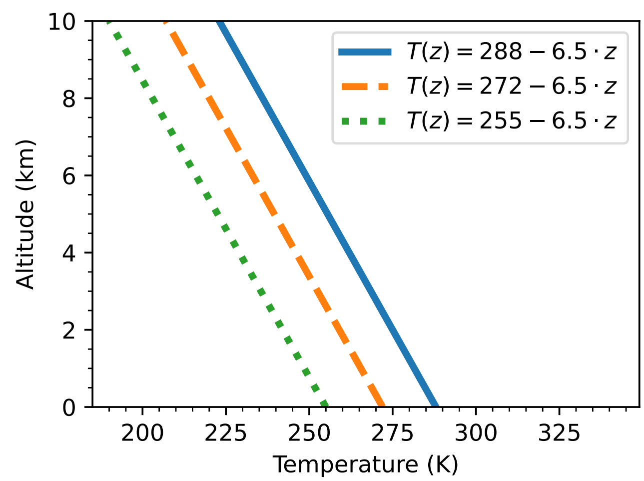

Figure 2: *Variation of temperature with altitude. A given lapse rate can be associated with any surface temperature. Sample temperature profiles are shown for 3 different surface temperatures, each with the same lapse rate.*

Arrhenius's work was related to the surface temperature, T_s. These quantities are completely independent of one another.

The lapse rate (as implied by the work of Maxwell) is essentially the slope of a line; a slope does not specify how high or low that line is (as was considered by Arrhenius).

3.3 TG: Residual Temperature

Effective temperature is a measure of the radiative flux of thermal radiation. The effective temperature for a flux is the temperature that a black-body would need to have to emit that much radiation. For a given radiative flux, M, the associated effective temperature is $T_{M,e} = (M/\sigma)^{\frac{1}{4}}$ where σ is the Stefan-Boltzmann constant.

In discussions of planetary temperature, when the term "effective temperature" is used without any additional qualifiers, it refers to the *planetary effective temperature* association the flux of outgoing longwave thermal radiation, OLR, that a planet and its atmophere sends into space,

$$T_e = (\mathrm{OLR}/\sigma)^{\frac{1}{4}} \,. \tag{8}$$

For Earth at present, $T_e = 255$ K [12].

Holmes [1] defines what he calls the "residual" near-surface atmospheric temperature:

> "residual meaning the difference between the effective, (that predicted by S-B black body law), and the measured actuality. . . "

In other words, Holmes defines the residual, ΔT_{res}, as

$$\Delta T_{\mathrm{res}} = T_{sa} - T_e \tag{9}$$

where $T_{sa} = 288$ K is the near-surface air temperature, so that $\Delta T_{\mathrm{res}} = 33$ K.

3.4 TG: Thermal Enhancement

Holmes [2] asserts that the temperature gradient he describes "constitutes a thermal enhancement," and writes:

> "it is proposed that the residual temperature difference between the effective temperature and the measured near-surface temperature, is a thermal enhancement caused by gravitationally-induced adiabatic auto-compression, powered by convection."

The problem with this hypothesis is that, as far as I can tell, *Holmes offers no evidence or arguments for it whatsoever!* I find none in either paper [1, 2].

What Holmes *does* offer is:

1. Arguments *against* the greenhouse effect. *(I will address these in the next section.)*
2. Arguments that convection, and what Holmes refers to as "adiabatic auto-compression of gases," give rise to a thermal gradient within in the lower atmosphere (i.e., the troposphere). *(This conclusion is well-known and undisputed.)*
3. Arguments that a significant temperature gradient arises in air in a gravitational field, even in the absence of convection. *(This hypothesis is controversial. But, I don't see how it makes the slightest difference, given that (a) there is convection in Earth's troposphere, and (b) it has already been agreed that Earth's troposphere has a temperature gradient, or "lapse rate" due to convection.)*

Point #1 doesn't affirmatively support the hypothesis; it mere attacks a different hypothesis. Points #2 and #3 argue for the existence of a temperature gradient due to convection and gravity.[8]

Yet, what seems to be entirely missing is any argument as to *how the existence of a temperature gradient explains the "residual" surface temperature difference* between the actual temperature and the planetary effective temperature.

Here is the problem: Having a thermal gradient simply means that there is some "lapse rate," or general decrease in temperature with increasing altitude. It tells us nothing at all about the "overall temperature":

- A planet could be very hot, with a thermal gradient, or very cold, with a thermal gradient.
- The thermal gradient could be associated with a surface temperature way above the planetary effective temperature; or it could be associated with a surface temperature way below the planetary effective temperature.

The mere existence of a thermal gradient tells us nothing about the size of the residual surface temperature, ΔT_{res}. This is illustrated in Figure 3.

Holmes [2] writes:

> "The new 'null' hypothesis of climate change being put forward here, is that in the case

[8] Note that convection and adiabatic heating and cooling do not add any thermal energy to a planet, overall, as is explained in Appendix A.1.

> of Earth, solar insolation provides the 'first' ∼255Kelvin – in accordance with the black body law; this being the 'effective' or the 'base' level. And a gravitationally induced thermal gradient caused by auto-compression provides the 'other' ∼33Kelvin, termed the 'residual', to arrive at the known and measured average global temperature of 288Kelvin."[9]

Yet, this is not a hypothesis in any meaningful sense..

In these papers [1, 2], Holmes does not offer any theory for actually predicting T_{sa} or ΔT_{res} (as opposed to indirectly measuring them).[10]

Thus, Holmes is not offering a testable hypothesis, so much as a vague *unsupported speculation that a hypothesis might exist, and might involve the ideas that interest him.*

Holmes [1, 2] does not propose any meaningful substitute for the greenhouse effect.

With regard to planetary surface temperature, the IGL is a measurement tool, not a theory with explanatory power. And the temperature gradient tells us only how rapidly temperature changes with altitude; by itself, the gradient tells us nothing about the value of the surface temperature or why it is higher than the planetary effective temperature.

4 Greenhouse Effect

4.1 GHE: Definition

Holmes [2] writes:

> "a tropospheric greenhouse effect (GHE); meaning an anomalous net warming from greenhouse gases like CO_2... has never actually been empirically measured, quantified and then attributed to GHG in any published, peer-reviewed scientific study to date."

This thoroughly false statement offers a clear indication that Holmes does not know much about the greenhouse effect.

It's likely to be helpful to start off defining the *greenhouse effect*.

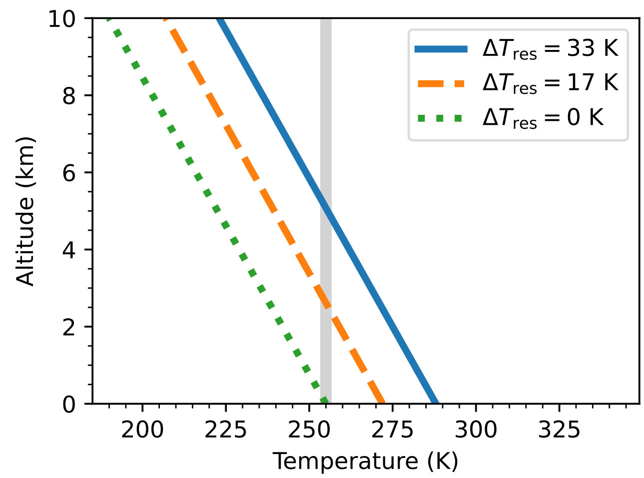

Figure 3: *A given lapse rate can be associated with any value of the residual $\Delta T_{\mathrm{res}} = T_{sa} - T_e$. Sample thermal gradients are shown for 3 different residual values (each with the same lapse rate and for $T_e = 255$ K).*

In technical work, *the "greenhouse effect" refers to the phenomenon of a planet emitting less thermal radiation to space* (denoted OLR) *than what is emitted by the planet's surface* (which will be denoted SLR, though this acronym is not standardized).

This difference between SLR and OLR is commonly quantified in one of three ways: as a flux difference

$$G = \mathrm{SLR} - \mathrm{OLR} \approx 158\ \mathrm{W/m^2} \qquad (10)$$

or as the *normalized greenhouse effect*

$$\tilde{g} = (\mathrm{SLR} - \mathrm{OLR})/\mathrm{SLR} \approx 0.40 \qquad (11)$$

or as the temperature difference[11]

$$\Delta T_g = T_{se} - T_e \approx 34\,\mathrm{K} \qquad (12)$$

between the *surface effective temperature*

$$T_{se} = (\mathrm{SLR}/\sigma)^{1/4} \qquad (13)$$

and the *planetary effective temperature* defined in equation (8) [19, 20, 18, 12].

[9] Footnotes in Holmes's passage reference Nikolov and Zeller [13]. Please see my response to that work in [14].

[10] Holmes does offer a recipe for actually predicting T_{sa} and ΔT_{res} (as opposed to indirectly measuring them) in a subsequent work, Holmes [15]. That recipe involves a separate additional hypothesis concerning total solar irradiance and temperature at a pressure of 1 atmosphere. That additional hypothesis is alluded to but is not fully developed in Holmes [2]. I respond to that hypothesis a separate response [16].

[11] The widely-quoted value 33 K is out-dated. It continues to show up because (a) it's a familiar value that everyone knows; (b) the temperature difference metric isn't used much by scientists, except informally; (c) in informal discussions of the greenhouse effect, it is easiest to refer to ΔT_{res} rather than to try to explain ΔT_g; and (d) 33 K arises as the result of a calculation which implicitly combines the atmospheric greenhouse effect (34 K) with a surface effect (–1 K) associated with variations in temperature [17]. The value 34 K quoted here is calculated using using recent data [12] and a rigorous definition of the greenhouse effect which separates the atmospheric and surface effects, in accordance with the usage in Haberle [18].

The metric used most commonly in climate science is the flux difference, G, although use of $\tilde{g}$ has significant advantages. The temperature difference metric is best known to the public, but seems to be used less often than G. Sometimes, less rigorous versions of the temperature difference metric might be used.

The surface effective temperature, T_{se}, is around 1 K higher than the near-surface air-temperature, T_{sa}.

The definitions of Holmes's "residual," ΔT_{res}, and the greenhouse effect temperature difference, ΔT_g, are only slightly different—for casual use, the distinction is just a technicality. They are marginally different ways of quantifying the same idea: the difference between the surface temperature and the planetary effective temperature.

It is valid to use G, $\tilde{g}$, or ΔT_g to characterize the greenhouse effect. (I often prefer to use $\tilde{g}$, for technical reasons, and because it is intuitively easy to understand: the value $\tilde{g} = 0.40$ tells us that 40% less thermal radiation reaches space than what leaves Earth's surface.)

If a greenhouse metric is greater than zero, that is what it means for a planet to *have a greenhouse effect*.

Holmes's claim that there are no peer-reviewed studies that empirically measure and quantify the greenhouse effect, and attribute it to greenhouse gases, is ludicrously wrong. For a sampling of such studies, see Appendix C.1.

Holmes [2] writes:

> "the residual near-surface atmospheric temperatures on planetary bodies with thick atmospheres are not mainly determined by the GHE, but instead are very likely caused by an effect from fluid dynamics, namely; autocompression."

Given the definition of the greenhouse effect, that statement is a non-sequitur. The *greenhouse effect* is the *name given to the difference between the surface temperature and the planetary effective temperature.* So, at a level of definitions, it is impossible for that difference to be "not mainly determined by the GHE."

The difference between the actual and effective temperature *is the GHE* (aside from technicalities regarding how the surface or near-surface temperature is measured).

I suspect that what Holmes really meant to argue is that the GHE is *not mainly due to greenhouse gases or absorption and emission of longwave radiation*.

That would at least be a coherent assertion—albeit one that is easily proven to be false, as will be explained in the next section.

4.2 GHE: Background

Holmes [2] offers numerous arguments which claim to offer evidence against the greenhouse effect. Each of those arguments rests on misunderstandings of the greenhouse effect.

It may be useful to summarize some additional key points related to the greenhouse effect.

1. The existence of the greenhouse effect is not some vague untestable idea, but a matter of measuring SLR and OLR and calculating whichever greenhouse effect metric one prefers to use (G, $\tilde{g}$, or ΔT_g). If the metric is greater than zero, then a greenhouse effect is said to exist.
2. A greenhouse effect has been observed to exist on Earth, Venus, Mars, and Titan [21, 22, 18, 23, 16].
3. This phenomenon (OLR $<$ SLR) is provably related to the presence of materials within the atmosphere capable of absorbing thermal radiation (i.e., greenhouse gases and clouds). *Proof:*[12] If nothing in the atmosphere is capable of absorbing or scattering thermal radiation then all thermal radiation emitted by the surface must reach space; in other words, without such materials, OLR $=$ SLR and $G = 0$.
4. This phenomenon also relies on the existence of a thermal gradient within the atmosphere. Solving the radiative transfer equation (see #5) shows that if the atmosphere was uniformly the same temperature as the surface then it would also be the case that OLR $=$ SLR and $G = 0$, even if the atmosphere had abundant greenhouse gases.[13]
5. The greenhouse effect depends on thermal radiation at the boundary of space (OLR) and thermal radiation emitted by the surface (SLR). The relationship between these two may be calculated if one knows the surface temperature and emissivity and the atmospheric composition and temperature profile. All one needs to do is to apply the laws of physics which describe how radiation changes as it propagates through a partially-transparent medium. These laws are described by the radia-

[12] Proofs are typically found in mathematics, not in science. Yet, science is built on mathematics. This is essentially a mathematical proof, which could be formalized by considering the definition of *absorptance*, the relationship of the absorptance of an atmosphere to the *absorptivity* of its constituent gases, and the definition of a *greenhouse gas* or *greenhouse material* as being a gas or material with non-zero absorptivy.

[13] This does *not* mean that the greenhouse effect *causes* thermal gradients. Nor does it mean that *only* the thermal gradient cause the greenhouse effect. The greenhouse effect is the result of both greenhouse gases and the thermal gradient, acting together.

tive transfer equation. *One can directly calculate the size of the greenhouse effect by solving this equation*. When calculating radiative transfer within the troposphere under clear-sky conditions, one may use a form of this equation called *Schwarzchild's equation for radiative transfer*.[14] The Schwarzchild equation cares about only the thermal radiation *absorption and emission properties of the air*, and the atmospheric temperature profile. This offers additional confirmation that the greenhouse effect depends on greenhouse gases. [24, 25, 26, 27, 28]

6. If there are both greenhouse gasses and a temperature gradient with temperatures decreasing with increasing altitude, then the radiation transfer equation indicates that there *must be a greenhouse effect*.

Thus, the existence of a greenhouse effect is well-defined quantitatively, and relies on both (a) the presence of greenhouse materials (gases or water droplets or ice particles capable of absorbing thermal radiation), and (b) the existence of a temperature gradient within the troposphere.

However:

- There is no claim that the greenhouse effect *causes* the temperature gradient in the lower atmosphere. The temperature gradient is well-understood to be primarily *the result of convection* (and associated adiabatic cooling of ascending air and warming of descending air).[15]
- There is no claim that radiative heat transfer is the dominant form of heat transfer within the troposphere. To the contrary, the greenhouse effect is associated with (but is not defined by) the *suppression of radiative heat transport* within the troposphere. A strong greenhouse effect is associated with strong suppression of radiative heat transfer.[16]
- The greenhouse effect is *not about heat transfer within the atmosphere*; the greenhouse effect is about a *reduction in the efficiency of heat loss to space.*[17] It is concerned with energy/heat flows at the interface with space, and the relationship of those flows to surface temperature—but (perhaps surprisingly) that relationship can be computed without explicit reference to heat transfer within the atmosphere, so long as one knows the atmospheric temperature profile.

4.3 GHE: Thermal Gradients

Some incorrect arguments in Holmes [2] are rooted in the false belief that climate scientists attribute thermal gradients to the greenhouse effect (GHE):

- "Less well known is that this rising temperature gradient continues even below the surface making it problematic to attribute this thermal gradient to the GHE."
- "Whatever hypothesis is used to explain the Earth's temperature... it must explain how a universal atmospheric thermal gradient and enhancement that is widely attributed to the action of a wholly above-surface GHE, can still continue on with its gradient unchanged, to below the surface level as it does in a mine-shaft. And how this same gradient/enhancement appears in atmospheres with virtually no greenhouse gases present."[18]

Given that the GHE is not claimed to be the cause of thermal gradients, those arguments are invalid.

4.4 GHE: Venus

Holmes asserts:

> "There has always been difficulty in explaining, or in formulating a simple method to satisfactorily explain or calculate the very high surface atmospheric temperature of the planet Venus using conventional mathematical means or by employing the greenhouse gas hypothesis."

Yet, to the contrary, planetary scientists and climate scientists have no difficulty in doing this. The temperature of Venus is confusing only to those who misunderstand how the greenhouse effect functions.

Holmes raises a number of specific concerns:

[14] When scattering by clouds or aerosols is important, some additional terms must be added to the transfer equation.

[15] Radiative cooling in the upper troposphere does contribute to convection happening, by providing a high "cold sink" for heat transported upwards via convection.

[16] Despite this suppression, radiative heat transfer is remarkably strong in the atmosphere, as is discussed in Appendix A.2. See Appendix C.2 for an illustration of what would happen in the absence of that suppression.

[17] Those might sound like the same thing, but they are *not*. It takes time to understand the difference, which is subtle but important.

[18] Holmes does not identify which atmospheres he imagines have "virtually no greenhouse gases present." All planetary atmospheres in our solar system contain significant quantities of greenhouse gases. The four giant planets are estimated to have 0.5-3.3% greenhouse gases in their atmospheres, with methane being the most common greenhouse gas [29].

#1 Holmes questions whether a super-critical fluid, as is present in the lower atmosphere, can contribute to the GHE. However, all that is needed to participate in the GHE is that a material be capable of absorbing and emitting thermal radiation. There is no requirement that the material act like a gas. The lower portions of Venus's atmosphere exhibit "continuum absorption", meaning that they absorb radiation over a very broad range of longwave wavelengths [22]. Thus, the criteria for acting as a greenhouse material is fully met.

#2-4 Holmes expresses concerns about Venus not absorbing much sunlight (due to a high albedo), not receiving much sunlight at the surface (due to low shortwave transmissivity to the surface), and not receiving sunlight continuously (due to the long day length). However, none of these issues are significant.

The greenhouse effect doesn't rely on any particular rate of incoming energy being present. It is a phenomenon involving the rate of heat leaving being low—or extremely low in the case of Venus. This conserves whatever incoming energy is available.

One important point is that incoming energy only needs to match the *heat flux* leaving, not the upwelling radiation flux. The *radiative heat flux is the net energy transfer after the downwelling radiation flux is subtracted from the upwelling radiation*.

The lower atmosphere of Venus is essentially opaque to thermal radiation, which means that upwelling and downwelling radiation are nearly identical, and the radiative heat flux is nearly zero. A high temperature is all that is needed for the flux in each direction to be high; there is no need for the rate of incoming energy to be high, so long as the difference between the radiation flux in the two directions is matched by the incoming energy flow.

#5 Holmes wonders how the GHE is affected by the high rotation speed of Venus's atmosphere, and speculates that this might lead to feedbacks that would eliminate the warming effect of the GHE. This is unfounded speculation. The greenhouse effect relates to the propagation of thermal radiation within an atmosphere. Motion of an atmosphere does not affect its radiative properties.

Holmes asserts that a "conventional 'GHE' of the type described by the IPCC is not possible" since less than 20 W/m² of direct solar insolation reaches the surface and since the atmosphere is so hot that it radiates at a rate of 15,000 W/m² at the surface. However, as was described above, these numbers pose no problems. All that is necessary is that the rate of radiative heat loss at the surface be no larger than 20 W/m². This implies a downwelling heat flux at the surface of between 14,980 and 15,000 W/m². This is easily achieved, since the super-critical-fluid atmosphere is about as hot as the surface and is opaque to thermal radiation—which means the lower atmosphere radiates as an extremely hot black-body. So, contrary to Holmes's claim, the numbers in no way rule out a "conventional 'GHE'."

While the above arguments question the existence of a greenhouse effect on Venus, it is simple to apply the quantitative *definition* of the greenhouse effect to determine whether such an effect exists.

The surface of Venus has a temperature of about 737 K and a planetary effective temperature of 227 K [30]. These imply a surface-emitted longwave radiation flux SLR $= \sigma T_s^4 = 16,730$ W/m^2 (a bit higher than the value offered by Holmes); and an outgoing longwave radiation flux OLR $= \sigma T_e^4 = 150$ W/m^2.

Thus, the greenhouse effect metrics for Venus are $G = 16,580$ W/m^2; $\tilde{g} = 0.99$; and $\Delta T_g = 510$ K.

The amount of thermal radiation emitted to space is 99% lower than the amount emitted by the surface.

So, it is quantitatively certain that Venus has a very large greenhouse effect.

4.5 GHE: Alleged Assumptions

Holmes writes

> "The existing null hypothesis of climate change simply assumes that there exists a 33°C 'residual' warming effect, which in turn is assumed to be 100% produced by GHG in the lower troposphere."

That statement is highly misleading. There are no "assumptions" involved. There are only measurements and rigorous logic:

- There is a specific quantity, $\Delta T_g = T_{se} - T_e$, which is *measured* to have a value $\Delta T_g \approx 34$°C.[19]
- As has been described previously, very simple logic establishes that this value can be nonzero

[19]Some climate skeptics dispute the accuracy of measurements of SLR and OLR (or misleadingly claim that there are no measurements). Yet, is it remotely plausible that values estimated as 398 and 240 W/m^2 could turn out to be *equal*, as would be needed in order to eliminate the greenhouse effect? Multiple lines of reasoning easily falsify any extraordinary claim of there being such a large error.

> only if there are materials in the atmosphere capable of absorbing thermal radiation. (Gases that have this capacity are called "greenhouse gases." Clouds also have this capacity.) If there were no such materials in the atmosphere, then the atmosphere would by definition be transparent to thermal radiation, and all thermal radiation emitted by the surface would necessarily reach space, leading to zero greenhouse effect. For more about this, see Appendix C.2.

Subsequently, Holmes writes

> "it is suggested that the 'null' hypothesis for climate, as presently understood, is invalid because it includes a very significant influence from an effect which has merely been assumed and has not been empirically detected, quantified or attributed and has not been shown to exist in the real atmosphere - namely, anomalous tropospheric warming from so-called 'greenhouse' gases."

That statement is false in every respect:

- The greenhouse effect has not "merely been assumed."
- The greenhouse effect has been empirically detected, quantified (as G, $\tilde{g}$, or ΔT_g), and has been measured to exist (i.e., have a positive non-zero value) in the atmospheres of Venus, Earth, Mars, and Titan. ΔT_g is precisely the "anomalous tropospheric warming" that Holmes is doubting.
- Simple logic makes it impossible for this effect to not be associated with gases capable of absorbing thermal radiation, i.e., greenhouse gases.

4.6 GHE: Calculating Surface Temperature

Holmes [1] writes:

> "It has always been complicated mathematically, to calculate the average near surface atmospheric temperature on planetary bodies with a thick atmosphere. Usually, the Stefan Boltzmann (S-B) black body law is used to provide the effective temperature, then debate arises about the size or relevance of additional factors, including the 'greenhouse effect'."

Contrary to Holmes's assertion, this calculation is in some ways remarkably simple.

The *planetary effective temperature*, T_e, is a function of the outgoing longwave radiation flux, OLR, as defined by equation (8). We can relate T_e to the surface temperature, T_s, simple by making some definitions.

We define the *planetary effective emissivity* by

$$\epsilon_e = \frac{\text{OLR}}{\sigma\, T_s^4}\,. \tag{14}$$

Then, we separate the *planetary effective emissivity*, ϵ_e, into a product of the *surface effective emissivity*,

$$\epsilon_{es} = \frac{\text{SLR}}{\sigma\, T_s^4}\,. \tag{15}$$

where SLR is thermal radiation emitted by the surface; and the *atmospheric effective emissivity* which we can write as $\epsilon_{ea} = (1-\tilde{g})$. So,

$$\epsilon_e = \epsilon_{ea}\cdot\epsilon_{es} = (1-\tilde{g})\,\epsilon_{es}\,. \tag{16}$$

This relationship provides an implicit definition for $\tilde{g}$. An equivalent, more explicit, definition is $\tilde{g} = 1 - \text{OLR}/\text{SLR}$.

Applying these emissivity definitions leads to

$$\text{OLR} = (1-\tilde{g})\,\epsilon_{es}\,\sigma\, T_s^4\,. \tag{17}$$

Applying the definition of T_e from equation (8) to equation (17) and solving for T_s leads to:

$$T_s = \frac{T_e}{\sqrt[4]{(1-\tilde{g})\,\epsilon_{es}}}\,. \tag{18}$$

So, we see that the surface temperature is related to the planetary effective temperature via the fourth root of the surface's effective emissivity, ϵ_{es}, and the atmosphere's effective emissivity, $\epsilon_{ea} = (1-\tilde{g})$. The quantity $\tilde{g}$ is conventionally called the *normalized greenhouse effect*.

Contrary to what Holmes suggests, equation (18) shows that expressing *the relationship between the surface temperature and the planetary effective temperature is very simple*.

Note that there was no physics at all involved in the derivation of equation (18). All that was needed was to define various quantities, and then write an equation that expresses their relationship. Equation (18) is *inherently true*, by virtue of the way that the quantities $\tilde{g}$ and ϵ_{es} are defined.

So, there is no question as to whether the greenhouse effect is involved in the relationship between surface temperature and the planetary effective temperature. *It is true as a matter of definition.*

The "greenhouse effect" is not a theory. It is the name of a quantified observed phenomenon.

The only theory involved is the connection of the observed phenomenon (i.e., the greenhouse effect) to underlying physics.

One could simply measure OLR and $\tilde{g}$ and ϵ_{es} and use those values to calculate T_s. However, to be able to have a theory with explanatory and predictive power, it is helpful to:

1. Relate the *planetary effective temperature* to the amount of energy received by the planet.
2. Relate the *normalized greenhouse effect* to the properties of the atmosphere.

Issue #1, relating OLR and T_e to other quantities, may be addressed as follows.

A planet gains energy via absorbed solar radiation, ASR, and via non-solar heating, NSH (though, on Earth, non-solar heating is negligibly small [31]). A planet can lose thermal energy to space only via outgoing longwave thermal radiation, OLR. (We're not talking about energy movement into or within the atmosphere, but energy leaving the planet altogether.)

If energy arrives faster than it leaves, then energy accumulates on the planet (including the surface, oceans, and atmosphere) at a rate EI (which stands for "Energy Imbalance"). This is required by the principle of conservation of energy.[20] Thus:

$$\mathrm{OLR} = \mathrm{ASR} + \mathrm{NSH} - \mathrm{EI}\,. \tag{19}$$

Consequently, the planetary effective temperature can be expressed as

$$T_e = \sqrt[4]{\frac{\mathrm{ASR} + \mathrm{NSH} - \mathrm{EI}}{\sigma}}\,. \tag{20}$$

That is why one will often see it claimed that $T_e = (\mathrm{ASR}/\sigma)^{\frac{1}{4}}$, which is valid if NSH and EI are negligibly small.

Issue #2, relating $\tilde{g}$ to atmospheric properties, may be addressed as follows.

As inputs to the calculation, one needs to know, or assume values for:

- The flux, SLR, and spectral radiance of *thermal radiation emitted by the surface*. This can be calculated if one knows the temperature of the surface and the material it is made out of. Values for this are also measured.
- The thermal radiation spectral *absorption coefficient* of the atmosphere, as a function of altitude. This is easily computed from the known spectral properties of gases, if one knows the composition of the atmosphere, as a function of altitude.
- The *temperature profile* (temperature at each altitude) of the atmosphere.

Given these inputs, the laws of physics say that the propagation of thermal radiation is governed by the radiative transfer equation [24, 25, 26, 27, 28]. Solving this equation can be done (a) analytically if one makes simplifying assumptions about the atmosphere, or (b) numerically given realistic information about the atmosphere. Solving the equation yields a value for OLR, which leads to a value for $\tilde{g}$.

Examining the radiative transfer equation makes it obvious that if nothing in the atmosphere can absorb thermal radiation, then $\tilde{g}$ is zero.

The basic form of the radiative transfer equation was first published by Karl Schwartzchild in 1906 [33]. This equation may be shown to be a direct consequence of Einstein's quantum theory of radiation [34, 28]. The radiative transfer equation is a very well-established physical law, which has been applied and verified in countless scientific and industrial applications [27].

Thus, the process for computing the greenhouse effect, based on underlying atmospheric properties, rests on a very solid foundation.

4.7 GHE: Arrhenius

It is puzzling why Holmes imagines that critiquing Arrhenius is relevant to the correctness of modern climate science. The work of Arrhenius was based on imperfect understandings.

Arrhenius's key 1896 paper was published a decade before the first appearance (in 1906) of Schwartzchild's equation for radiative transfer, which is essential for quantitative analysis of the greenhouse effect [35, 33]. Arrhenius worked 70 years before Syukuro Manabe and collaborators laid the foundation for modern planetary temperature analysis in the 1960s.

The work of Arrhenius was wrong in a number of respects, due to the limitations of what scientists then knew. Later scientists thought for themselves, rejected what was wrong, and kept only what held up under

[20] This result can also be obtained by applying the *First Law of Thermodynamics*, which says that for a closed system, $\mathrm{EI} = \Delta U_{\mathrm{system}} = Q - W$, where Q is net heat flow into the system and W is mechanical work done by the closed system on the system outside it [32]. To apply this to a planet, imagine a conceptual spherical boundary around the planet outside its atmosphere. The system inside the boundary is a thermodynamically closed system. Because the boundary is in vacuum, no mechanical work can be done on the outside system; hence $W = 0$ and $\mathrm{EI} = Q$. The net heat flow into the system is $Q = \mathrm{ASR} + \mathrm{NSH} - \mathrm{OLR}$. Equation (19) follows.

subsequent analysis. So, even if additional flaws were found in the work of Arrhenius, that would not necessarily indicate anything at all regarding the quality of *modern* scientific thought on these topics.

Nonetheless, let's look at what Holmes writes:

> "One of the main problems with the Arrhenius view, is that radiative transfers are emphasised, and convection is virtually ignored as a mode of heat transfer."[21]

Arrhenius did not "ignore" convection as a mode of heat transfer. He simply assumed, for the purpose of his analysis, that heat transfer due to convection would *not change* as the concentration of atmospheric CO_2 was changed:

> "Likewise we will suppose that the heat that is conducted to a given place on the earth's surface or in the atmosphere in consequence of atmospheric or oceanic currents, horizontal or vertical, remains the same in the course of the time considered... It is only the variation of the temperature with the transparency of the air that we shall examine." [35, p. 254]

While such an approach oversimplifies reality, it is a perfectly reasonable approach to use when first trying to understand a subject.

Possibly Holmes's complaint, though nominally directed at Arrhenius, reflects a belief that modern discussions of the greenhouse effect give too little attention to convection as a mode of heat transfer?

Let's consider the applicability of Holmes's critique to a modern analysis of the greenhouse effect, such the one offered in Section 4.6 (or in Wentworth [36]).

That analysis does not mention heat transfer due to convection at all! And, despite appearances, it doesn't mention radiative heat transfer within the atmosphere either.

So, the analysis doesn't "ignore" convection; it's simply that *heat transfer within the atmosphere is not relevant* to the analyses, as surprising as that might be.

The analysis considers three things:

1. *Energy or heat flow across a conceptual boundary placed above the atmosphere*, in a place where radiation is the only available mechanism for transferring thermal energy. (This is part of the calculation of T_e.) Radiative heat transfer is the only heat transfer mechanism that operates in space.
2. The planetary *surface's emission of upwelling thermal radiation*. (This is an input to the calculation of $\tilde{g}$.) This is *not* "heat" leaving the surface, as the term "heat" is defined in thermodynamics. Radiative heat flow is the *net energy flow* after the flux of downwelling radiation is subtracted from the flux of upwelling radiation. So, while upwelling thermal radiation is *related* to heat flow, *upwelling thermal radiation is not "heat."*[22]
3. The *relationship between the amount of thermal radiation that leaves the surface and the amount that reaches space*, i.e., determination of $\tilde{g}$, the fraction by which radiation emitted to space is reduced relative what left the surface. Determining $\tilde{g}$ involves either (a) simply treating $\tilde{g}$ as an empirically-determined quantity or (b) solving for the propagation of radiation through the atmosphere. No heat flow analysis is involved; it is just about the propagation of thermal radiation, which as mentioned above, is *not heat flow* (even if it bears some relationship to heat).

The structure of the analysis may take some time to begin to make sense. Yet, whether you understand the argument or not, it should be possible to see that *heat flow within the atmosphere is not considered anywhere in the analysis*; it's not what the analysis is about.

So, convective heat flow is not being "ignored." It's simply that this is *not the sort of analysis that involves heat flow within the atmosphere*, even if you might have expected it to be that sort of analysis.

The core argument is ultimately about conservation of energy. A planet and its atmosphere will accumulate energy, and thus increase its temperature, if less energy is leaving to space than is entering. A planet and its atmosphere will lose energy and decrease in temperature, if more energy is leaving to space than is entering. Thus, the temperature of a planet can be relatively stable only if the rate of energy leaving to space approximately equals the rate of energy arriving.

The greenhouse effect is simply a characterization of to what degree the flux of energy flow into space (OLR)

[21] Holmes's comment continues with "Yet later work shows that not more than 11% of heat transfer in the troposphere is actually carried by radiation." As explained previously, the greenhouse effect is associated with *suppression of radiative heat transfer* in the lower atmosphere. So, radiative heat transfer being small would *not* be an argument against the greenhouse effect. That said, the 11% statistic relates only to radiative heat transfer to air near the surface; in general the radiative heat flow in the troposphere is far larger, per Appendix A.2. Radiative cooling is eventually 100% of heat flow, and this is important in the troposphere.

[22] Even if you balk at accepting the thermodynamical nuance that upwelling thermal radiation is not considered to be heat, the main point is that the analysis doesn't care about *total heat flow* except in #1 at the interface with space, where radiative heat flows are the only heat flows that can exist.

is smaller than the flux of thermal radiation emitted by the surface (SLR). The details of what happens in between the surface and space doesn't matter for purposes of analyzing planetary temperature, so long as we know the relationship between those two quantities, as characterized by $\tilde{g}$.

4.8 GHE: Atmospheric expansion

Holmes writes:

> "Thermodynamics demands that if more CO_2 were to start to 'create' an anomalous warming through forcing, then this must result in atmospheric expansion, because warmer air expands. But this would increase potential energy at the expense of kinetic energy - so cooling the air again."

Holmes argues that atmospheric expansion constitutes a feedback that would counter the greenhouse effect.

Holmes fails to appreciate that this phenomenon is already accounted for in the distinction between the constant-volume heat capacity, C_v, of a gas and the constant-pressure heat capacity, C_p.

For dry air (at 0°C), C_v = 0.7171 kJ kg^{-1} K^{-1} and C_p = 1.006 kJ kg^{-1} K^{-1} [37].

The constant-pressure heat capacity is larger than the constant-volume heat capacity because it accounts for the *work that must be done by warming air to lift the weight of the atmosphere above it*. That work goes into increasing the gravitational potential energy of the atmosphere. Thus, the effect Holmes is concerned about is fully accounted if one uses the *constant-pressure heat capacity* of air when doing any calculations involving atmospheric heat capacity.

However, heat capacities do not tend to alter equilibrium temperatures. They tend to simply alter how long it takes a system to reach its equilibrium.

The heat capacity of air is negligibly small in comparison with other heat capacities affecting Earth's approach to equilibrium (principally the heat capacity of upper layers of the ocean). Thus, the impact of atmospheric expansion on climate change can be dismissed as negligible.

5 Conclusions

Holmes [2] characterizes the process of applying the molar-mass form of the ideal gas law (IGL) to calculate temperature as procedure for "predicting" planetary surface temperatures. However, this procedure is in no way capable of anticipating what the temperature of a planet will become in the future, if the factors which influence planetary temperature are altered. The procedure can only do so if some other theory (with more explanatory power) is first used to predict the future atmospheric density.

Thus, the way that Holmes applies the IGL more closely matches the characteristics of *procedure for indirectly measuring temperature* than those of a theory capable of *predicting* temperature.

Holmes [2] claims to calculate the climate sensitivity or temperature increase associated with doubling that atmospheric concentration of CO_2. However, that calculation functions by virtue of making an unjustified assumption which implicitly *assumes* that the temperature change will be small, leading to the calculation of a small and meaningless result.

Holmes offers no valid insights into climate sensitivity in response to increases in atmospheric greenhouse gases.

Holmes seems to mistakenly believe that the existence of temperature gradients in the atmosphere due to convection (a phenomenon well-known to climate scientists) somehow explains planetary surface temperature, eliminating any need to take the greenhouse effect into account. Yet, the gradient (or lapse rate) only explains the rate of change of temperature between different altitudes. It offers no information on the overall temperature of the atmosphere and surface. Thus, it does not account for planetary temperature. Nor does it explain the "thermal enhancement" that Holmes calls the "residual" temperature and climate scientists refer to as the "greenhouse effect," i.e., the amount by which the surface temperature exceeds the planetary effective temperature.

Holmes [2] offers no testable hypothesis to explain the "residual temperature." All that is offered is a completely unsupported speculation that thermal gradients might somehow explain it.

Holmes seems to mistakenly believe that climate scientists attribute temperature gradients to the greenhouse effect. Yet, it is universally accepted among atmospheric and climate scientists that the thermal gradient in the lower atmosphere is primarily due to convection. So, the finding by Holmes that the thermal gradient is due to gravity and convection is not in any conflict with scientists' understanding of the greenhouse effect.

Holmes offers a number of additional criticisms of the greenhouse effect and of Arrhenius as one of those who first offered insights about the greenhouse effect. Each of those criticisms was seemingly rooted in one or more misunderstandings.

Holmes's belief that there can be no "conventional" greenhouse effect on Venus was shown to be entirely based on misunderstandings of how the greenhouse effect functions.

Holmes appears to be unfamiliar with the greenhouse effect being a well-quantified observable phenomenon which, by its very definition, influences surface temperature. The difference between the surface temperature and the planet's effective temperature, is named the "greenhouse effect."

Holmes questions whether greenhouse gases could cause that temperature difference. However, his reasoning for questioning that premise is rooted in his invalid application of the IGL using unjustified assumptions and circular reasoning.

Simple logical arguments, as well as reference to the well-established and long-validated radiative transfer equation, make it clear that greenhouse materials (i.e., gases which absorb and emit thermal radiation, and clouds) are essential to the existence of a greenhouse effect.

Overall, Holmes [2] offers no viable theory and fails to justify any of its major claims.

A Appendix: Thermal Gradient Side Issues

A.1 TG: Kelvin-Helmholtz Contraction

Contrary to what Holmes [2] suggests, there are important differences between 'auto-compression' associated with convection and the 'Kelvin-Helmholtz' contraction which heats stars during their formation process:

- Kelvin-Helmholtz contraction involves a lowering of mass into the gravitational well of a (typically new) star or planet, transforming gravitational potential energy into heat. In this process, there is a net movement of matter "downward," resulting in a net loss of gravitational potential energy and an increase in total thermal energy. Thus, the Kelvin-Helmholtz contraction process is a *source of thermal energy*.
- Convection within an atmosphere involves equal movements of mass upwards and downwards. Ascending air transforms thermal energy into gravitational potential energy, cooling the air. Descending air transforms gravitational potential energy into thermal energy, warming the air. When both ascent and descent are considered, there is no net change in the altitude of mass within the gravitational well. As a result, there is no net release of heat in this process. Thermal energy gained by downward-moving air is always equaled by thermal energy lost by upward-moving air. A temperature gradient is created, but *convection and adiabatic "auto-compression" do not add any additional thermal energy to the system overall.*

Kelvin-Helmholtz contraction is believed to be heating Jupiter, which is estimated to be shrinking by about 1 mm/year [38].

Saturn is believed to be heated by a related mechanism: helium (heavier) condenses into a liquid and sinks towards the center of the planet while hydrogen (lighter) rises; the net effect is a lowering of mass, transforming gravitational potential energy into thermal energy [38].

It is known that Earth is not contracting and is *not* experiencing Kelvin-Helmholtz heating [39].

A.2 TG: Dominance

Holmes [1] writes:

> "The adiabatic auto-compression hypothesis enunciated herein, states that convection/pressure/lapse rate effects dominate over radiative effects in regions of all planetary atmospheres >0.1 bar and a temperature gradient is naturally formed. In effect, gravity forms a density and a temperature gradient; pressure is a corollary."[23]

Holmes does not define what he means by saying that "convection/pressure/lapse rate effects *dominate* over radiative effects."

It is true that convection plays a major role in shaping the atmospheric temperature profile up to the tropopause.

However, radiative cooling matches non-radiative heating throughout the troposphere, as is illustrated in Figure 4(b).

Heat flow is being transformed from non-radiative heat flow to radiative heat flow throughout the troposphere, as is illustrated in Figure 4(a).

Above a few kilometers in altitude, the radiative heat flow exceeds the non-radiative heat flow.

[23] Once gravity and convection establish the temperature gradient, pressure and density are jointly set by the combination of the hydrostatic equilibrium equation, $dP/dz = -\rho g$, and the ideal gas law. Pressure and density play equally important roles in this; I'm not aware of any sense in which "pressure is a corollary" as Holmes asserts.

So, while Holmes is correct that convection plays a central role in shaping the temperature profile in the troposphere, he would have to define what he means more carefully before it would be safe to say that convection effects "dominate" over radiative effects.

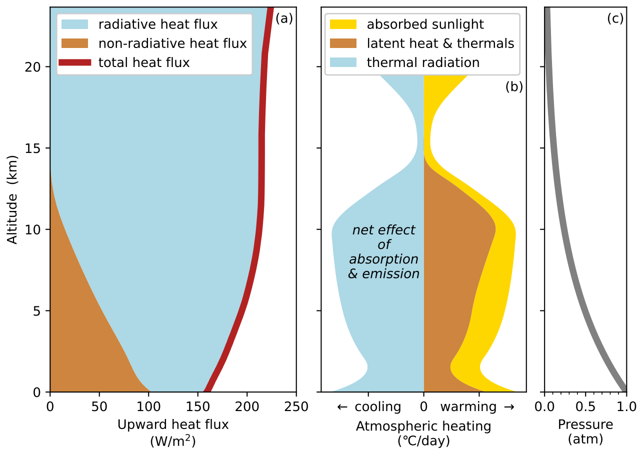

Figure 4: *Atmospheric heat flow.* ***Panel (a)*** *shows upward heat flux versus altitude. Near the surface, non-radiative heat flow associated with convection (carrying water vapor and warm air) accounts for about two-thirds of the total heat flux, with radiative heat flow accounting for the remainder. As altitude increases, non-radiative heat flow decreases, vanishing above the tropopause. Radiative heat flow (which is always upward) increases with altitude, as non-radiative heat flow is converted to radiative heat flow. The total upward heat flux increases with altitude as a result of sunlight being absorbed in the atmosphere; the heat from absorbed sunlight must find its way back towards space, and so leads to an increase in the upward heat flow.* ***Panel (b)*** *shows the heating and cooling of air, measured in units of temperature change, not heat flow. It takes little heat flow to produce a large temperature change in the thin air at higher altitudes. Non-radiative heating is provided by convection, via thermals carrying warm air and water vapor that condenses and releases latent heat. Air is also warmed via absorption of sunlight; about a third of absorbed sunlight is absorbed by the atmosphere rather than by the surface. On average, heating and cooling are in balance. Cooling is provided by greenhouse gases emitting thermal radiation. At all altitudes, greenhouse gases tend to emit more thermal radiation than they absorb.* ***Panel (c)*** *shows the drop in pressure with altitude. (Plots are based on data adapted from [40]. Panel (b) is related to figures in Manabe and Strickler [41].)*

B Appendix: IGL Molar Mass and Pressure Changes

Holmes [2] estimates that doubling the concentration of atmospheric CO_2 from 0.04% to 0.08% should increase pressure by 0.04% and molar mass by 0.05%, with molar mass being increased from 28.97 to 28.984.

Those values are incorrect, as is shown by the following analysis:

1. The concentration of CO_2 in the atmosphere is measured as a percentage (or fraction) by volume or moles. CO_2 has a molar mass 1.52 times larger than air [42]. So, an increase by moles of 0.04% corresponds to an increase by mass of 0.061%. Thus, if CO_2 increases by 0.04% by volume and nothing else changes, then the mass of the atmosphere would increase by 0.061% while moles in the atmosphere increase by 0.04%. This yields an increase in molar mass (i.e., mass divided by moles) by 0.021%.
2. The CO_2 added to the atmosphere is most often produced by: the decomposition of organic matter, respiration, or combustion of hydrocarbons. If any of these processes is involved, then the carbon is being newly added to the atmosphere but the oxygen incorporated in the CO_2 was previously in the air as O_2. Thus, a realistic calculation should probably combine a 0.04% molar increase in CO_2 with a 0.04% molar reduction in O_2.
3. If we wish to include both an increase CO_2 and an equal molar decrease in O_2, then the total number of moles in the atmosphere would not change at all. But, the mass of the atmosphere would change by a factor of 0.04% times $(44-32)/29$ where 44, 32, and 29 are the molar masses of CO_2, O_2, and (dry) air, respectively. That is a net mass increase of 0.017%. Thus, molar mass would increase by 0.017%.
4. Global mean surface pressure corresponds to the total weight of the atmosphere divided by the surface area of the planet. So, to determine the change in global mean surface pressure pressure, one simply needs to compute the change in the weight of the atmosphere. The change in mass was

already calculated in the steps above. So, if CO_2 is increased without any change in O_2, pressure would increase by 0.061%. If the increase in CO_2 is accompanied by an equal molar decrease in O_2, then pressure would increase by 0.017%.

In summary, for molar mass, M, and pressure, P, with a 0.04% molar increase in the amount of CO_2 in the atmosphere:

1. *If O_2 remains the same:* M increases by 0.021%; P increases by 0.061%.
2. *If O_2 decreases by 0.04%:* M increases by 0.017%; P increases by 0.017%.

Neither scenario leads to numbers which match Holmes's prediction that M increases by 0.05%; P increases by 0.04%.

C Appendix: GHE Supplemental

C.1 GHE: Studies Measuring and Attributing

Here is a sampling of studies which provide counter-examples to the assertion in Holmes [2] that there are no peer-reviewed studies that empirically measure and quantify the greenhouse effect, and attribute it to greenhouse gases:

1. The first thing to notice is that, given the definition of the greenhouse effect in Section 4.1, measuring the GHE is simply a matter of measuring the flux of longwave thermal radiation at the surface (SLR) and outgoing to space (OLR). These have both been measured, on an ongoing basis, for decades. Loeb et al. [43] and Kato et al. [44] describe how the NASA CERES project has measured, analyzed, and calibrated these fluxes since the year 2000.[24]
2. Data on SLR and OLR are translated into estimates of the greenhouse effect and are shown to match models based on the effects of greenhouse gases by Kiehl and Trenberth [45] and Sejas, Taylor, and Cai [46].
3. Additional modeling to support attributing greenhouse effect observations to greenhouse gases is presented in Schmidt et al. [47] and Schmithüsen et al. [48].
4. Haberle [18] applies radiative models to explaining the observed greenhouse effect on Mars, and McKay, Pollack, and Courtin [23] do this for Titan.
5. Analysis of the greenhouse effect in terms of atmospheric gases involves calculating the detailed spectrum of radiation reaching space under a wide variety of circumstances. Haskins, Goody, and Chen [49] offer numerous measured spectra from a number of distinct geographic regions, and present technical information useful to associating these with with the "vertical distribution of... temperature, water vapor, and clouds" (all factors expected to impact the greenhouse effect).
6. Turner et al. [50] offers measured spectra of downwelling longwave radiation reaching the surface, along with matching modelled spectra; although this does not directly address the main greenhouse effect, it demonstrates the accuracy of radiative modeling.
7. While not a journal article, Chicago [51] illustrates how radiative transfer calculations based on assumed greenhouse gas distributions can replicate the spectrum of outgoing thermal radiation as measured in space.
8. Figures 5 and 6 show how the greenhouse effect metrics have increased over the period 2000-2023, according to NASA CERES data.[25]

It is possible someone might complain that these studies don't demonstrate "warming" of the sort that they were wanting to see demonstrated. If so, the fault lies in the expectations. The greenhouse effect temperature difference, ΔT_g, *is the warming that is attributed to greenhouse gases.* These studies do measure that—or equivalent information, such as the flux difference G (sometimes confusingly referred to as "radiative forcing") or thermal radiation spectra—and attribute it to greenhouse gases.

C.2 GHE: Effect of Not Absorbing Thermal Radiation

Figure 7 illustrates the greenhouse effect, and what would happen to both the greenhouse effect and surface temperature if the ability of materials in the atmosphere to absorb thermal radiation was somehow turned off.

[24] I know some climate skeptics dispute these measurements, but at the moment I'm simply offering evidence of information appearing in peer-reviewed journal articles.

[25] These figures have not been peer-reviewed, but rely on NASA data.

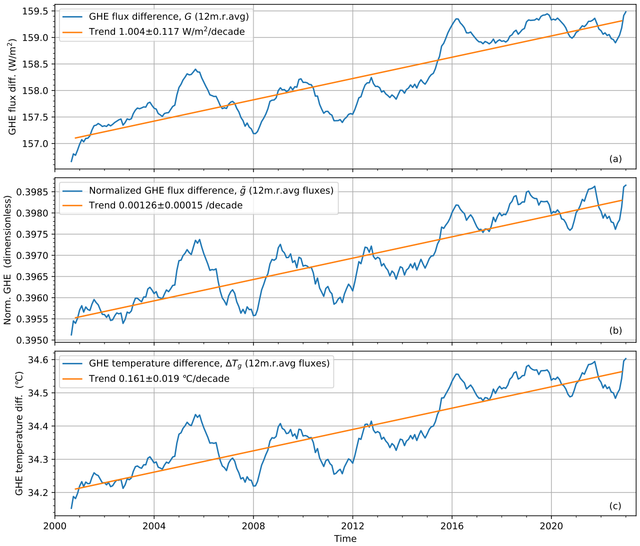

Figure 5: *Growth of (a) flux difference, (b) normalized GHE, and (c) temperature difference* ***greenhouse effect metrics*** *over the period 2000-2023, under* ***all-sky*** *conditions (i.e., both cloudy and cloud-free). (Based on NASA CERES EBAF Ed4.2 data. Fluxes have been subjected to a 12-month rolling average, to remove seasonal effects.)*

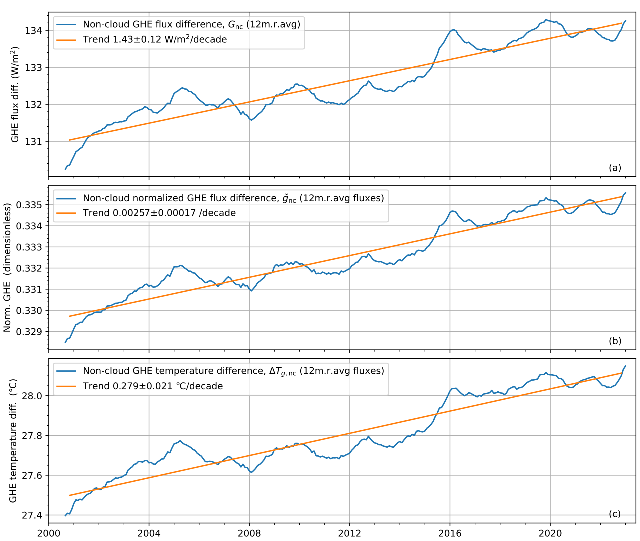

Figure 6: *Growth of (a) flux difference, (b) normalized GHE, and (c) temperature difference* ***greenhouse effect metrics*** *over the period 2000-2023, under* ***clear-sky*** *conditions (i.e., no clouds). (Based on NASA CERES EBAF Ed4.2 data. Fluxes have been subjected to a 12-month rolling average, to remove seasonal effects.)*

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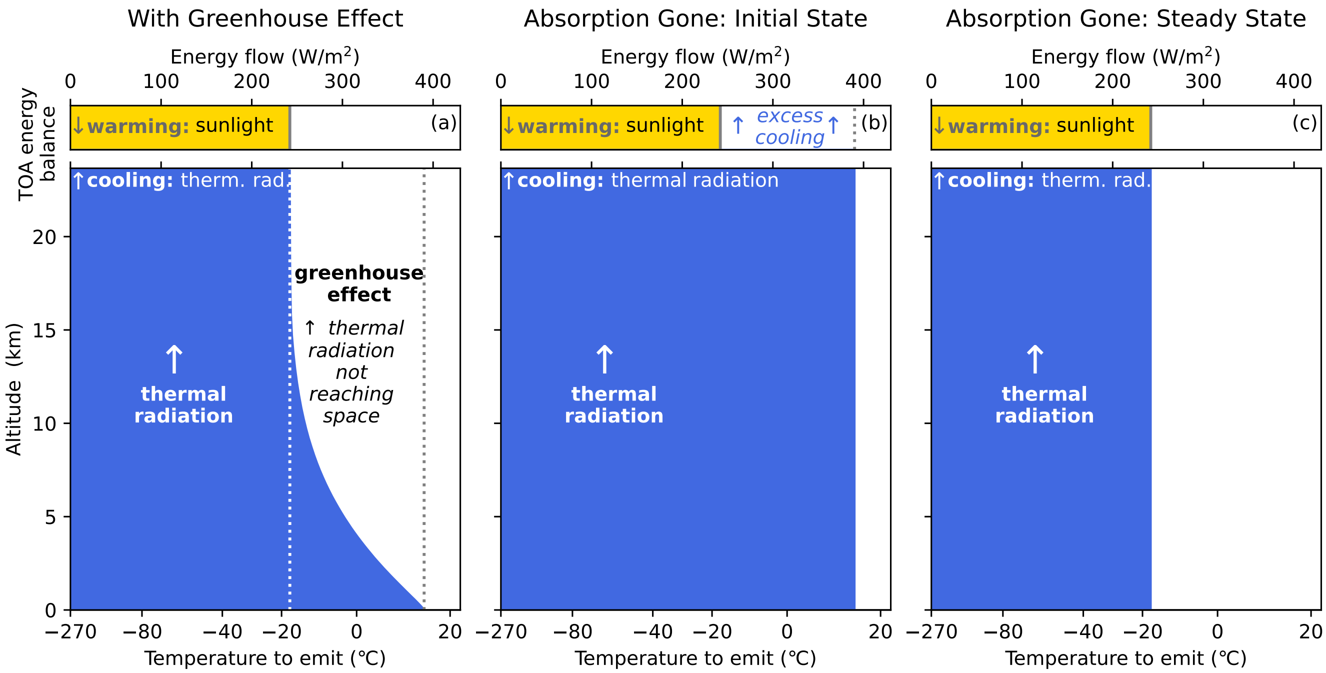

Figure 7: *The greenhouse effect is any reduction in upwelling thermal (longwave) radiation emitted to space relative to what leaves the surface. On Earth, this reduction is about 40% or 158 W/m^2.* ***Panel (a)*** *shows the radiative flux of upward longwave thermal radiation versus altitude. This flux is high at the surface, but decreases with altitude. This decrease in upward thermal radiation is the phenomenon referred to as the greenhouse effect. In steady-state, the amount of thermal radiation escaping to space matches the amount of energy received by the planet from absorbed sunlight.* ***Panels (b) and (c)*** *illustrate what would happen if the ability of greenhouse gases and clouds in the atmosphere to absorb and emit thermal radiation was suddenly "turned off" somehow.* ***Panel (b)*** *shows the initial state, immediately after absorption stops. Given that the surface would be at the same temperature, the surface would emit the same amount of thermal radiation; but since the atmosphere is now transparent to thermal radiation, the radiation emitted by the surface would all reach space (i.e., there would be zero greenhouse effect); Earth would be losing energy much faster than it arrives, so energy would drain away and the planet would cool rapidly.* ***Panel (c)*** *shows the state after a new thermal equilibrium has been reached, with energy once again escaping to space at the same rate as energy arrives via absorbed sunlight; the new equilibrium surface temperature would be much colder than the equilibrium surface temperature in panel (a).* ***Upwards thermal radiation vs. radiative heat:*** *The upward thermal radiation flux plotted in this figure is not the same thing as the radiative heat flow depicted in Figure 4; the radiative heat flow is the upward thermal radiation flux minus the downward thermal radiation flux. So, the upward thermal radiation flux and the radiative heat flow are the same thing only when the downward thermal radiation flux is zero, as happens at the top of the atmosphere in panel (a) or at all altitudes in panels (b) and (c).*

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