Basic Climate Physics #1

One fact at a time

This short essay is the first in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

The first topic pertains to thermal equilibrium, meaning equilibrium with sunlight. At the orbit, sunlight has a certain intensity I_{sun}—often called *solar flux*—measured in (thermal) watts per square meter. Some fraction α (albedo, the reflectivity) of that is reflected, and the remaining fraction $(1 - \alpha)$ is absorbed. Averaged over the $4\pi R^2$ surface area, then, $I_{in} = \frac{I_{sun}}{4}(1-\alpha)$ is absorbed by the planet.

Jupiter seems to have a heat source (a modicum of nuclear fusion?) at its core, and some moons of the large planets receive a significant amount of energy from tidal forces, but with those exceptions, all of the planets (and their satellites) are in equilibrium with sunlight. That is, the emit just as much heat radiation as they receive from the sun: $I_{out} = I_{in}$. Of course, the heat radiated from the planet is in the infrared (IR) range, whereas the sunlight is mostly in the visible range. This equality leads to a very important equation that applies to all planets (even around all suns) that are in equilibrium with sunlight:

Planetary Heat Balance

$$I_{out} = \frac{I_{sun}}{4}(1-\alpha)$$

There is nothing new or unique about the Planetary Heat Balance equation. What I want readers to see and understand is that **the radiation to space I_{out} depends on exactly two variables, the intensity of sunlight and the albedo**. Of course, I_{out} can change, but only if either sunlight changes or the albedo changes.

Again, we are talking about equilibrium conditions. Disequilibrium can occur. If, for example, I_{in} exceeds I_{out}, then the planet warms up until a new equilibrium is achieved. My motivation is (in future short discussions) to address the *Equilibrium* Climate Sensitivity (ECS), the term used by the IPCC and others for the temperature rise of the surface of the earth due to a doubling of CO_2 concentration.

Some numbers

At 149.6 million kilometers from the sun, our planet is exposed to sunlight at about 1,366 W/m² (give or take a little), and our albedo is 0.3, so we absorb and radiate about 239 W/m². (Published numbers vary between 239 W/m² and 244 W/m²).

By contrast, the solar flux at Venus, at 108.2 million km from the sun, is a bit over 2,600 W/m². The planet reflects 75% of that light, so that the planet absorbs and radiates about 162 W/m². Venus, which is very hot at its surface, emits less IR to space than does the earth.

An important Rule of Measurement

Measure the distance from your feet to the moon. Then measure the distance from your head to the moon. Now determine your height by subtraction. You might find out that you are negative 477 meters tall.

The general rule is that whenever possible measure differences directly, rather than obtaining them by subtraction.

In the case of an imbalance between heat absorbed from the sun and IR radiated to outer space, there is no direct way to measure the difference between the two numbers. The small imbalance must be obtained by subtraction of two large numbers, both subject to uncertainties. IPCC finds (in its *Fifth Assessment Report, AR5*) that the earth absorbs more from the sun than it emits. The amount they come up with is 0.6 ± 0.4 W/m². The uncertainty is almost as big as the quantity itself. In any case, the imbalance is a very small fraction of the 239 W/m² absorbed and emitted.

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Basic Climate Physics #2

One fact at a time

This short essay is the second in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

Terminology: The greenhouse effect

The greenhouse effect in a real greenhouse was initially thought to be due to the fact that visible light would enter the greenhouse, but the glass would block outgoing infrared (IR). Fleagle [1] refers to a 1909 experiment by Johns Hopkins University physicist Robert W. Wood who substituted rock salt for glass because it is transparent to IR and showed that it is just about as effective as glass in keeping the greenhouse warm. He found the greenhouse effect to be due mostly to the fact that the greenhouse is a confined space through which warm air was blocked from rising.

In the case of the atmosphere, the visible/IR explanation comes a lot closer to the truth, but it is still somewhat deficient. Again, the source of energy is the sun. The surface warms up and radiates IR. Certainly, the radiation to space is less than the surface radiates, but the interactions are many and complex. Greenhouse gases—we'll consider the five GHGs (H_2O, CO_2, O_3, CH_4, and N_2O) analyzed by van Wijngaarden and Happer [2]—absorb IR according to their own spectra. The absorbed energy excites vibrational/rotational modes in the molecules. That excess energy can be shed by collisions with other molecules (most likely N_2 and O_2), contributing to general heating of the region. They can also emit IR in random directions.

The process of radiating IR is often incorrectly called *reradiation*, somehow implying that the number of photons is constant (it is not), or that the molecule radiated once and does it again.

Molecular collisions can also excite GHGs into vibrational/rotational states that can radiate IR. In fact, thermal equilibrium requires that a certain temperature-dependent percentage of the molecules are in those states. The IR that goes into space is largely from this collision-induced radiation at high altitude where the GHGs are sufficiently sparse that the IR can escape.

The greenhouse effect is thus very complicated, and best comprehended by experts such as van Wijngaarden and Happer. However, a simplicity does emerge.

The IPCC has been discussing the greenhouse effect for three decades, and finally in its *Sixth Assessment Report* [3], has assigned a symbol G to the term and calculated its value: 159 W/m². The symbol disguises its close relationship to the "radiative forcing" ΔF, which is merely a difference in G.

Simple subtraction

The arithmetic version of G is that it is the simple numerical difference between the IR flux emitted by the surface and the IR flux emitted to space: $G = I_{surf} - I_{out}$. In the *Fifth Assessment Report*, the values in the equation were $I_{surf} = 398$ W/m² and $I_{out} = 239$ W/m², with the difference being $G = 159$ W/m². The equation $G = I_{surf} - I_{out}$ is the important basic physics lesson in this essay. Remember it.

More elaborate subtraction

Infrared involves a spectrum. Notice that the vertical axis in Figure 2 has units of W/m² • cm, and the horizontal axis is in numbers of wavelengths per cm (cm⁻¹ sometimes called wavenumbers). A vertical strip between two wavenumbers, as shown schematically to the right, thus has an area in units of W/m². The area under the whole curve represents the total amount of IR.

In Figure 1, the total area under the smooth curve represents the total IR emission from the surface. The total area under the jagged black curve represents the total IR emission to space. The total area between the smooth curve and the

400   450
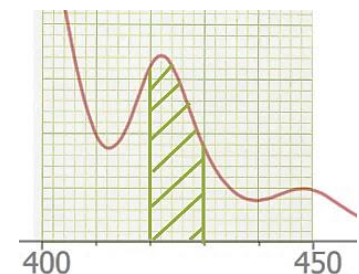
jagged black curve represents the net blockage (retention) or IR energy due to all atmospheric effects combined. Figure 2 shows the graphical version of $G = I_{surf} - I_{out}$
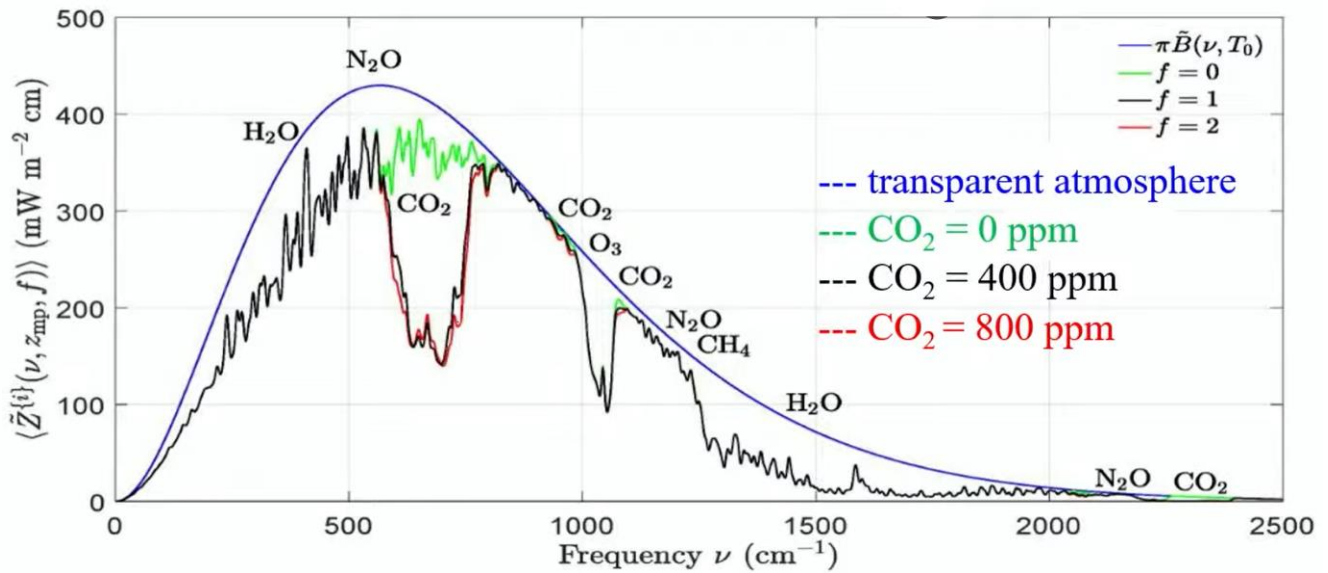

Figure 1: The smooth blue line represents the IR emitted by the surface of the earth. The jagged black line represents the IR emitted to space. The jagged green line represents what the black line would look like if all things were the same, but there was no CO_2 in the atmosphere. The red line represents the change in emission to space if the CO_2 concentration doubles. (Adapted from van Wijngaarden and Happer [2].)

We will discuss the matter further in the next short essay, but note that the effect of doubling CO_2 concentration is represented by the tiny area between the jagged black curve and the jagged red curve.
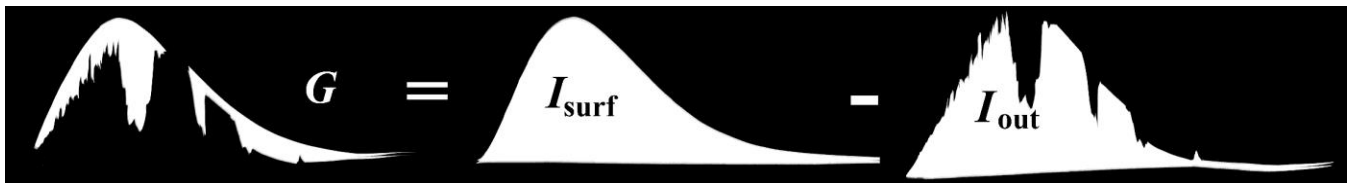

Figure 2: Graphical representation of the greenhouse effect.

Conclusion

All verbiage aside, the greenhouse effect is the readily calculable difference between the IR emission at the surface and the IR emission to space.

$$G = I_{surf} - I_{out}$$

Presently, G is (using IPCC data) 159 W/m². CO_2 is responsible for about 30 W/m² at present.

References

[1] Robert G. Fleagle and Joost A. Businger, The "Greenhouse Effect," *Science*, 12 December, 1975
[2] W. A. van Wijngaarden1 and W. Happer, "Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases," (arXiv:2006.03098v1 4 June 2020)
[3] All IPCC reports are available as PDFs at https://www.ipcc.ch/. *The Sixth Assessment Report* is presently (October 2021) incomplete.

Basic Climate Physics #3

One fact at a time

This short essay is the third in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

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IPCC's Inept Physics

As you read the statement to the right from the IPCC, you get the feeling that they're shaking a pillow feather in your face. They introduce a symbol α_P without defining it, but tell us that the variable helps stabilize the climate. But their ignorance of physics shows up in the last clause: "a warmer planet radiates more energy to space."

The clue to the fundamental physics error in the statement to the right is to be found in IPCC's *First Assessment Report* (*FAR* 1990), which said

> "Firstly, the mean temperature of the Earth's surface is already warmer by about 33°C (assuming the same reflectivity of the Earth than it would be if the natural greenhouse gases were not present."

The Planck response represents the additional thermal or longwave (LW) emission to space arising from vertically uniform warming of the surface and the atmosphere. The Planck response α_P, often called the Planck feedback, plays a fundamental stabilizing role in Earth's climate and has a value that is strongly negative: a warmer planet radiates more energy to space.
> IPCC, *6th Assessment Report* (*AR6*, 2021)

Translation: Given the assumption that the reflectivity (albedo) of the earth is constant, the hypothetical non-GHG planet absorbs precisely the same amount of heat from the sun as the earth does now and radiates that same amount into space. The surface is 33°C warmer than that hypothetical non-GHG earth, *but our hotter planet radiates precisely the same amount of energy to space.*

For a second example, consider Venus. The surface is hot enough to melt lead, but because of its very high albedo of 75%, the planet absorbs 156 W/m² from the sun and emits 156 W/m² to space, versus our 239 W/m². *In this case, the hotter planet radiates less energy to space.*

QED!

Stefan-Boltzmann radiation law

The spectrum of blackbody radiation was well known in the middle-to-late 1800s. The Stefan-Boltzmann radiation law tells us the total amount of radiation emitted, and Planck's equation (1900) tells us the spectral distribution (how much IR at what photon energy). The atmosphere is not a blackbody, but solid materials and liquids are. That is, the earth's surface is a blackbody radiator.
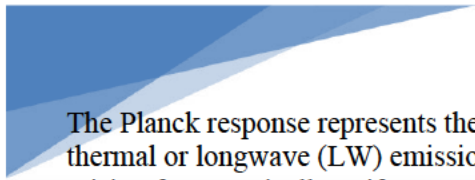
Specifically,

$$I_{\text{surf}} = \varepsilon \sigma T^4$$

In this equation, the coefficient $\sigma = 5.67 \times 10^{-8}$ W/m² per K (or per °C). The intensity is in watts per square meter, and the temperature is in Kelvins. The *emissivity* ε of the earth averages about 0.94, but climate scientists usually take it to be 1.0. To find how much the emission varies with temperature, we find the differential, including the emissivity for completeness:
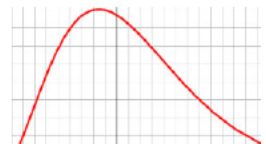
$$dI = 4\varepsilon \sigma T^3 dT$$

At a temperature of 289 K, the coefficient of dT is 5.47 W/m² per °C with $\varepsilon = 1$, and 5.14 W/m² per °C with $\varepsilon = 0.94$. Citing various investigators, IPCC's *AR6* says,

Overall, there is *high confidence* in the estimate of the Planck response, which is assessed to be $\alpha_P = -3.22$ W m^{-2} °C^{-1} with a *very likely* range of –3.4 to –3.0 W m^{-2} °C^{-1} and a *likely range* of –3.3 to –3.1 W m^{-2} °C^{-1}.

These IPCC estimates *assume* that approximately 40% of the additional heat radiated from a warmer surface stays within the earth and 60% of the additional heat goes into space. (IPCC's minus signs indicate outgoing heat.)

Summary

It is clear that the IPCC has some serious misunderstandings about basic physics. The lesson in this short essay is that the radiation from the surface of the planet (for that matter *any planet*) is determined by the Stefan-Boltzmann radiation law. We will discuss the radiation to space in the next essay.

More importantly, the next essay will summarize the physics of the first two lessons and insert the Stefan-Boltzmann law to produce one all-inclusive equation that will not predict future climate, but will tell us what *cannot* happen.

Modelers, BEWARE!

Basic Climate Physics #4

One fact at a time

This short essay is the fourth in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

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Review of first three lessons

Lesson 1: All planets radiate the same amount of heat that they get from the sun.

Planetary Heat Balance

$$I_{out} = \frac{I_{sun}}{4}(1-\alpha) \tag{1}$$

This equation applies to any planet going around any star (sun), so long as the only heat source is the star. The albedo (reflectivity) is represented by α.

Lesson 2: The greenhouse effect is the difference between the surface radiation and the radiation to space.

$$G = I_{surf} - I_{out} \tag{2}$$

This equation applies to any planet that has a surface and any atmosphere of any kind whatsoever (including none).

Lesson 3: The surface radiation is given by the Stefan-Boltzmann radiation law.

$$I_{surf} = \varepsilon \sigma T^4 \tag{3}$$

Here, the emissivity ε is usually taken to be 1.0, although a more correct value is 0.95. We will stick with the IPCC's traditional 1.0 for simplicity. The Stefan-Boltzmann radiation constant is 5.67×10^{-8} W/(m^{2}K^4).

Simple algebra

It is a simple matter to combine Equations 1, 2, and 3 into one. Begin with Equation 2 and insert Equations 3 and 1 in sequence, and assume that the emissivity ε is 1.0:

Lesson 4:
$$G = \sigma T_{surf}^4 - \frac{I_{sun}}{4}(1-\alpha) \tag{4}$$

Equation 4 is just as all-inclusive as the other equations. It applies to Mercury, Venus, the Earth, and Mars, but not to the gaseous planets (no surface). It applies to most moons in the solar system, but not to a few that are heated by tidal forces owing to the proximity to massive planets.

Equation 4 has no capability of predicting the climate, but it can and does tell us what cannot happen.

At present, IPCC uses the following numbers for our planet: $T_{surf} = 289$K; $I_{sun} = 1366$ W/m^2; and $\alpha = 0.3$. With these numbers, the first term to the right of the equation is 398 W/m^2, and the second is 239 W/m^2, so that $G = 159$ W/m^2.

Now imagine a future IPCC (in 2322, for example) constructing a heat-flow diagram for the earth, akin to the type found in IPCC's *Fifth Assessment Report* (*AR5,* 2014). (*AR6* 2021remains incomplete as of February 2022.) Figure 1 shows the heat flow diagram from *AR5*, with external markings showing where the present numbers come from and how they would be determined at that future date. In other words, everything is now in accord with Equation 4, and will be at that time and all other times.
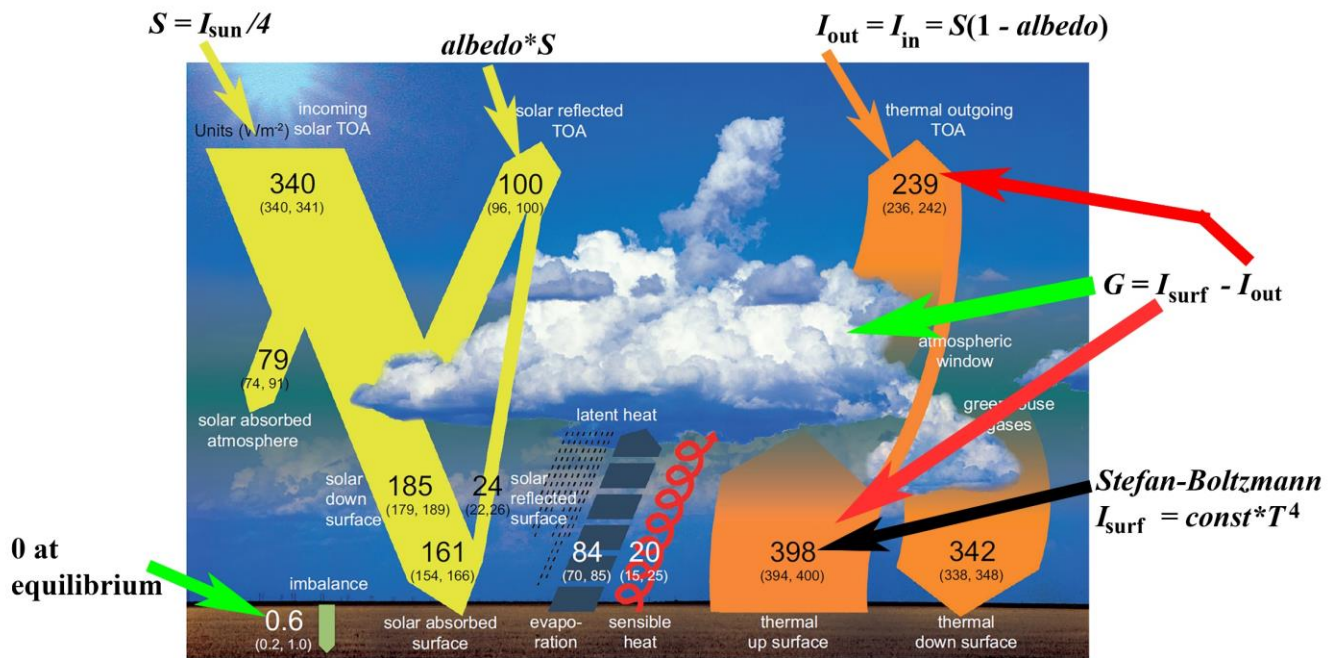
Figure 1: The heat-flow drawing from *AR5*, showing how the drawing comports with Eq. 4.

Now imagine that something changes. The greenhouse effect changes for some reason, the albedo changes for some reason, and/or the solar intensity changes. What does your climate model say the new temperature will be?

If your model gives a different temperature than you get from Equation 4, you'd better revise your model, because your model violates the law of conservation of energy. If your model does not produce values for all four variables— G, T_{surf}, I_{sun}, and α— it is woefully incomplete.

The next Climate Physics lesson will discuss examples.

Basic Climate Physics #5

One fact at a time

This short essay is the fifth in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

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The Energy Constraint on Climate (and models)

In Climate Physics Lesson 4, we summarized the basic physics of absorbed sunlight, surface IR emission, IR emitted to space in one equation with $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4)

$$G = \sigma T_{surf}^4 - \frac{I_{sun}}{4}(1-\alpha) \qquad (1)$$

There are precisely four variables in Eq. 1: the surface temperature T_{surf}, the solar intensity at orbit (often called the Total Solar Irradiance, *TSI*) I_{sun}, the albedo of Earth α, and the greenhouse effect G, which, despite the complicated physics involved, turns out to be the numerical difference between I_{surf} and the radiation to space I_{out}. The equation is sufficiently general that it applies to any planet or moon with any type of atmosphere, orbiting any sun, providing that the planet or moon has its sun as the only energy source, and a surface. In particular, it must apply to Earth however much fossil fuel we burn.

For example, at https://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html we find that the solar irradiance at Venus is 2601 W/m^2, and that the planet has an albedo of 76%. The rightmost term in Eq. 1, which represents the absorbed heat from the sun and the amount of IR emitted to space is 156 W/m^2. The surface temperature is 737 K, so the surface emission is 16,729 W/m^2, from which we conclude that the greenhouse effect on Venus is 16,573 W/m^2.

> As an aside, IPCC says, in the *Sixth Assessment Report* (*AR6*, 2021), "a warmer planet radiates more energy to space." Perhaps they never heard of Venus, or that is why they say **Do Not Cite, Quote or Distribute** on every page.

We are concerned, however, with Earth, for which the IPCC gives these numbers: $G = 159$ W/m^2; $T_{surf} = 289$ K; $I_{sun} = 1366$ W/m^2, and $\alpha = 0.3$.

> (These numbers vary somewhat depending on source—I am inclined to have higher trust in van Wijngaarden and Happer—but the overall conclusions are insensitive to the choice. At least IPCC cannot complain that I have used somebody's unapproved numbers.)

Lousy Nomenclature

Decades ago, climate modelers (& IPCC) adopted the term *radiative forcing*, with the symbology ΔF, to represent any increase or decrease in net IR blockage (stopping, reduction, …) due to changes in greenhouse gas concentrations in the atmosphere. Finally, in the **Do Not Cite, Quote or Distribute** *AR6*, the IPCC has made illusion to the *total* radiative greenhouse effect, and assigned the symbol G, and acknowledged that G is the difference between surface radiation and radiation to space. Clearly, then, the dramatic term *radiative forcing* is nothing more and nothing less than a positive or negative undramatic increment to G. That is, $\Delta F = \Delta G$ or dG.

Equilibrium climate sensitivity (ECS)

The term *equilibrium* in this case refers to the time when everything has settled down, and that happens when the planet emits just as much heat energy to space as it receives from the sun—precisely the conditions under which Equation 1 is derived. The term *equilibrium climate sensitivity* refers to the equilibriium temperature rise to be expected from a doubling of CO_2 concentration. Various climate models are based on guesses about how fast society will be increasing atmospheric concentration, most suggesting that doubling will take about a century.

But what the models have in common is the estimate of the "radiative forcing ΔF_{2xCO2}," due to changing CO_2 concentration, usually calculated from

$$\Delta F = 5.35\ln(C/C_0) \quad \left(\text{W/m}^2\right).$$

(2)

For a CO_2 doubling ($C/C_0 = 2$), the value is 3.7 W/m². (This may well be an overestimate, but we will continue to use IPCC values.)

Here is where the lousy nomenclature comes to the fore: the use of *radiative forcing* ΔF leads the non-technical person to fail to see that the 3.7 W/m² "radiative forcing" is a mere 2.3% addition to the greenhouse effect G of 159 W/m². Also, according to the IPCC, the surface is 33-34°C warmer than it would be with the same albedo but no greenhouse effect. In other words, 159 W/m² raised the surface temperature by 33-34°C. With CO_2 doubling, 162.7 W/m² is going to do *what?*

Examples

Most probable ECS?

The IPCC finds that the most probable temperature rise due to doubling CO_2 concentration is 3°C. If we use IPCC's "radiative forcing" for doubled CO_2, and assume that the intensity of sunlight at orbit remains constant, we get

or

$$G+3.7 = \sigma\left(T_{surf}+3\right)^4 - \frac{I_{sun}}{4}(1-\alpha) \quad \left(\frac{W}{m^2}\right)$$

$$G+3.7 = \sigma T_{surf}^4 + 16.5 - \frac{I_{sun}}{4}(1-\alpha) \quad \left(\frac{W}{m^2}\right)$$

(3)

If IPCC's prediction is correct, then somehow the –12.8 W/m² needed to balance Eq. 3 must be accounted for by a decrease in albedo and an increase in greenhouse effect from other gases. If anybody can find the details of how this is accomplished, please let me know. The experts to whom I have posed this conundrum have suddenly gone AWOL.

Glacial-Interglacial Transitions

If there is an iconic picture of the correlation between CO_2 concentration and surface temperature measured in ice cores at the Vostok site in Antarctica, it is surely that of Al Gore on a scissor lift showing how high CO_2 might get on his zero-suppressed graph. In approximate numbers, the temperature difference between the glacial periods and the interglacials is 10°C, and the CO_2 concentration ranged from 180 ppmv to 280 ppmv.

Equation 2 tells us that the "radiative forcing" (a.k.a. dG) for CO_2 is 2.4 W/m². The increase in surface radiation (Eq. 1) is about 55 W/m². Suffice it to say that Mr. Gore does not tell us how 2.4 W/m² of "radiative forcing" can cause the surface to increase its radiation by 55 W/m². For that matter, no climate modeler has provided an explanation either, but it strains the imagination to believe that they would give any credence to Mr. Gore.

Beyond the problem of trying to get the arithmetic to balance, there are the questions of where the CO_2 came from if it caused the temperature to rise and where it went if its decrease caused the temperature to fall. There is, of course, no quarrel with either the temperature rise or the increase in CO_2. It's about causality, and Mr. Gore has it all backwards.

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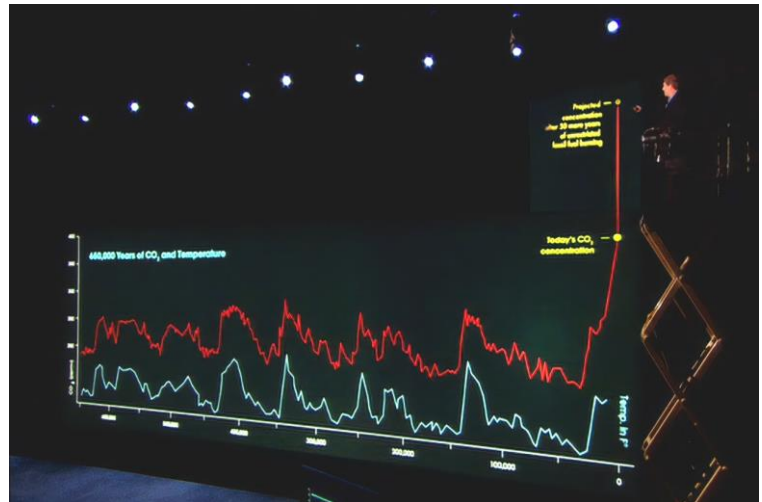
Basic Climate Physics #6

One fact at a time

This short essay is the sixth in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

We begin with a section from Basic Climate Physics #5:

The Energy Constraint on Climate: graphical version

In Climate Physics Lesson 4, we summarized the basic physics of absorbed sunlight, surface IR emission, IR emitted to space in one equation with $\sigma = 5.67 \times 10^{-8}$ W/(m²K⁴)

$$G = \sigma T_{surf}^4 - \frac{I_{sun}}{4}\left(1-\alpha\right) \tag{1}$$

There are precisely four variables in Eq. 1: the surface temperature T_{surf}, the solar intensity at orbit (often called the Total Solar Irradiance, *TSI*) I_{sun}, the albedo of Earth α, and the greenhouse effect G, which, despite the complicated physics involved, turns out to be the numerical difference between I_{surf} and the radiation to space I_{out}. Assuming, as IPCC does, that the *TSI* remains constant, Eq. 1 has three variables which can be graphed in various ways.

The figure to the right shows a graphical representation of Equation 1, with the red dot showing the present trilogy of albedo ($\alpha = 0.3$); greenhouse effect $G = 398$ W/m², and surface temperature $T_{surf} = 289$ K. Assuming that the sun remains constant, the slanting $T = 289$ K line represents the possible combinations of α and G that could produce the same surface temperature.
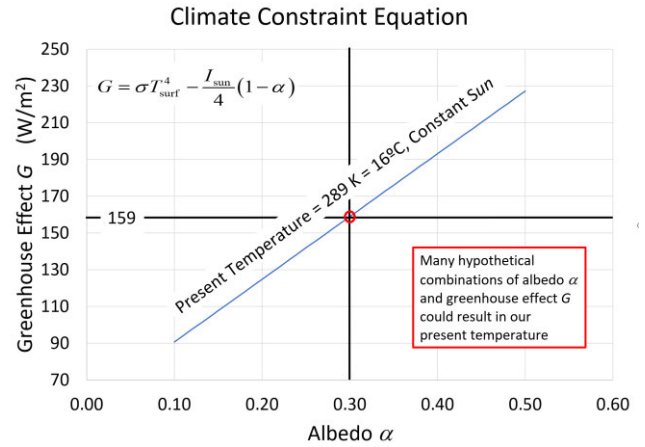
The Differential Form

The greenhouse effect in Eq. 1 is mostly due to H_2O, secondarily due to CO_2 (20%), and in small part to other GHGs. As we are interested in the "changing climate," let us find the differential of Equation 1.

$$dG = 4\sigma T_{surf}^3 dT_{surf} - \frac{dI_{sun}}{4}\left(1-\alpha\right) + \frac{I_{sun}}{4}d\alpha \tag{2}$$

Climate models try to predict future surface temperature increases due to increases in CO_2 concentration. Equation 2 *could* be used to calculate it, providing that the changes in the greenhouse effect, the solar intensity and the albedo were known. This is very unlikely.

Alternatively, if the models predict the surface temperature rise, the equation can—and *should*— be used to check whether the model is correct or incorrect; complete or incomplete. It is common in climate modeling to assume that sunlight remains constant. For simplicity, let us assume (as does the IPCC) that the TSI (I_{sun}) remains constant, and then rewrite Equation 2:

$$dG = 4\sigma T_{surf}^3 dT_{surf} + \frac{I_{sun}}{4}d\alpha \tag{3}$$

We can make a further simplification by using known present values: $\sigma = 5.67 \times 10^{-8}$ W/(m²K⁴), $T_{surf} = 289$ K and $I_{sun} = 1366$ W/m²:

$$dG = 5.47dT_{\text{surf}} + 342d\alpha \quad \left(\frac{\text{W}}{\text{m}^2}\right) \qquad (4)$$

Equation 4 has three variables: dG, dT_{surf}, and $d\alpha$, all representing changes from the present. We can now construct a graph of dG (ΔG, ΔF, "radiative forcing") on the vertical axis versus the albedo α on the horizontal axis, for various temperature changes, as shown in Figure 1.
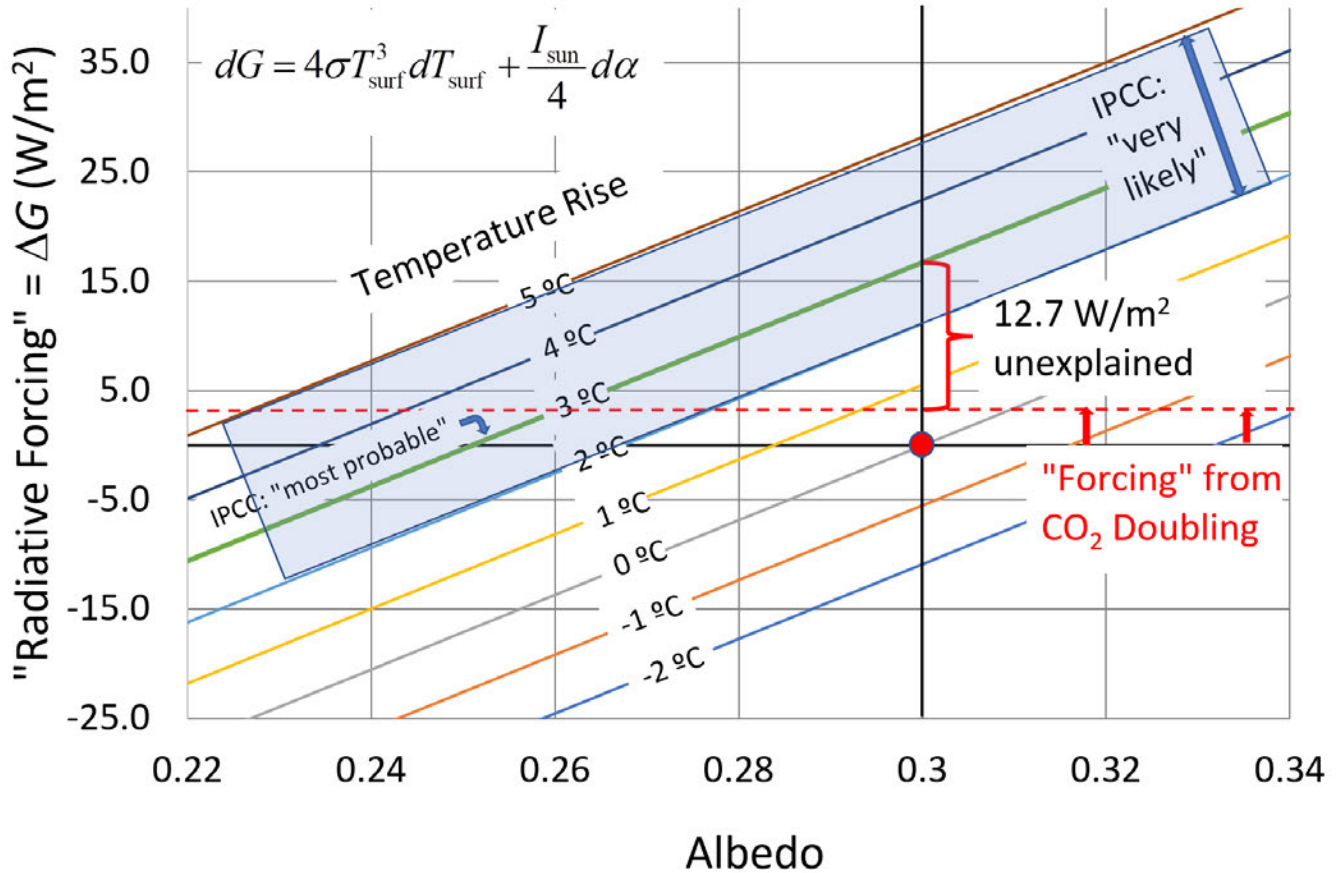

Figure 1: The differential form of the climate constraint equation. The red dot shows the current situation. The dashed red line shows the "radiative forcing" (=3.47 W/m², IPCC) due to doubling CO_2 concentration, and the green slanted line shows IPCC's "most probable" temperature rise of 3°C. IPCC says that the rise due to doubling is "very likely" to be between 2°C and 5°C. A temperature rise dT_{surf} of 3°C will increase surface radiation by 16.5 W/m². IPCC has no explanation and no description of how 3.47 W/m² can cause 16.5 W/m² of increased surface radiation.

In Figure 1, the dashed red line represents IPCC's "radiative forcing" due to CO_2 doubling. The slanted green line represents all possible combinations of albedo and "radiative forcing" that can result in a 3°C temperature rise (IPCC's "most probable" temperature increase due to CO_2 doubling). The slanted gray area represents IPCC's "very likely" range of temperature increase due to CO_2 doubling.

By the Stefan-Boltzmann radiation law, the surface radiation must increase as shown as the first term to the right of the equals sign in Equation 4. The results are in the table below.

Temperature increase (°C)	Increase in IR from surface (W/m²)	Increase in G due to CO₂ (W/m²)	Difference unaccounted for (W/m²)
2	10.9	3.7	7.2
3	16.4	3.7	12.7
4	21.9	3.7	18.2
5	27.4	3.7	23.7

If Equations 3 and 4 are to be balanced, it is clear that some combination of *increased* greenhouse effect from other GHGs and a *decrease* in albedo might—in principle—balance the equation. Climate models, however, all predict an *increase* in albedo with increased CO_2, and all show a totally inadequate increase in G from other GHGs to account for the increased surface emission. We will discuss that matter in the next Climate Physics lesson. We will uses IPCC's own data in *AR6* to prove that their models *cannot* balance the Climate Constraint Equation, and are therefore wrong.

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Basic Climate Physics #7

One fact at a time

This short essay is the seventh in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

Introduction

The Climate Constraint Equation relates the surface temperature to the albedo, the greenhouse effect, and the solar intensity. Accordingly, if the IPCC provides the albedo, the greenhouse effect, the solar intensity, and the surface temperature for at least one of its hundreds of scenarios, we can test to see whether the equation is balanced. As it happens, they seem to have done so, and they will not like the result.

IPCC's Predictions for Future Climate

Broadly speaking, IPCC makes two kinds of scenarios. First, they make models for how much CO_2 will be released as time progresses, thereby laying out the prediction of how much CO_2 will be in the atmosphere at any given date. Second, they make various assumptions about how that amount of CO_2 will affect things like evaporation rates, glacial melt, permafrost melt, and so forth.

They identify their models by the Shared Socio-economic Pathway (SSP) with two identifiers (SSPx-y): x for the chosen pathway, and y for the approximate level of "radiative forcing" (in W/m^2) expected in the year 2100 (compared to "pre-industrial values, ca. 1750). We will examine SSP3-7.0 (see Fig. 1) simply because it is one where CO_2 doubling takes place by 2100. We need data for temperature rise, albedo, and CO_2 concentration for some given time. The model SSP5-8.5, for example, has CO_2 doubling take place by 2050, but has the expected temperature rise in 2100, so it cannot be used.
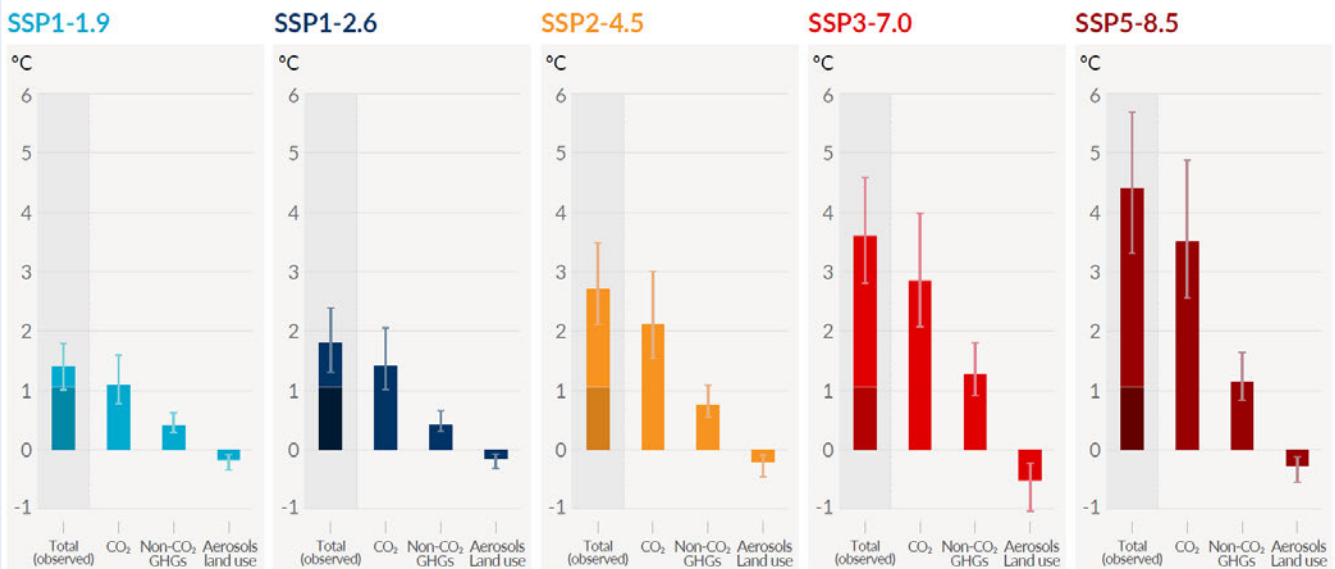
Figure 1: Five scenarios from the *Summary for Policy Makers* in the *Sixth Assessment Report* (*AR6*) in 2021.

Figure 1 shows measured temperature rises since 1850 (up to 2015) as the dark bars at the lower left in each case, and the temperature rises expected in each scenario by the year 2100 at Total (left bar), the amounts due to CO_2, other GHGs, and that due to changing albedo (via aerosols and land use) respectively. In all cases, of course, the temperature rise since 1850 is close to 1ºC. In all cases, an eyeball estimate shows that IPCC holds CO_2 responsible for close to 80% of the temperature rise, so our choice of the SSP3-7.0 case is not cherry-picking. The differences in the scenarios are primarily due to the choice of how fast society puts CO_2 into the atmosphere.

An annotated version of the SSP3-7.0 scenario is shown at the right. It shows a 3.6º temperature rise from 1850 until the last two decades of the present century, with 2.8ºC ascribed to CO_2, 1.25ºC ascribed to other GHGs, and –0.5ºC ascribed to an increase in albedo. That is the projected temperature rise due to GHGs is 4.1ºC, and that due to aerosols (reflecting more sunlight to space, hence to albedo) is –0.5ºC.

Given the assumption that the temperature in 1850 was 288 K, and the end-of-century temperature would be 291.6 K, the increase in surface IR should be 19.9 W/m². (Note that IPCC includes the change in reflected incoming sunlight with changes in net absorption of outgoing IR by GHGs in the dramatic term "radiative forcing.")

In 1850, the atmospheric CO_2 concentration was 285 ppmv. *AR6* asserts that the "radiative forcing" due to CO_2 from 1750 to 2019 is 2.72 [1.96 to 3.48] W/m², and says that the "effective radiative forcing" due to doubling is 3.93 W/m² (an increase from their previous estimate of 3.71 W/m²).

Let us put these numbers together. IPCC says that the *total human-caused* "radiative forcing" from CO_2 from 1750 to 2000 (in SSP3-7.0) is 2.72 + 3.93 = 6.65 W/m². If we further recognize that CO_2 accounts for 80% of the greenhouse effect, the total human-caused GH effect is 6.65/0.8 = 8.3 W/m².

IPCC Data Meet the Constraint Equation

To review: at equilibrium, the heat radiated to space equals the heat absorbed from the sun: $I_{out} = \left(\dfrac{I_{sun}}{4}\right)(1-\alpha)$,

where α is the albedo. Also, the IR flux to outer space equals the surface radiation minus the net absorption by the atmosphere (the greenhouse effect) G: $I_{out} = I_{surf} - G$. Let us equate these two values of I_{out}, and then find the differential, assuming a constant sun:

$$I_{surf} - G = \left(\frac{I_{sun}}{4}\right)(1-\alpha)$$

$$dI_{surf} - dG_{CO2} - dG_{other} = -\left(\frac{I_{sun}}{4}\right)d\alpha$$

(1)

As we saw above for SSP3-7.0 the increase in surface radiation (dI_{surf}, 1750-2100) due to GHGs should be 22.7 W/m², and the "radiative forcing" (increment dG to the greenhouse effect G) for the same period is 8.3 W/m².

Let us now use IPCC's numbers in Equation 1:

IPCC says for 2100: $\qquad 19.9 - 8.3 - dG_{non-human-caused} = \left(\dfrac{I_{sun}}{4}\right)d\alpha = 0 \quad \dfrac{W}{m^2}$ (2)

In equation 2, the zero enters because IPCC has included their notion of albedo change in the surface temperature change. Somehow, non-human-caused changes in the greenhouse effect (but not identified by the IPCC) must amount for 11.6 W/m² needed to balance Eq. 2. (Note that if we used the temperature rise since 1750 instead of 1850, the increase in surface radiation would be even higher.)

Obviously, IPCC's analysis of climate is woefully incomplete, if not egregiously in error.

The next lesson will address the adiabatic lapse rate—the drop in temperature versus altitude.
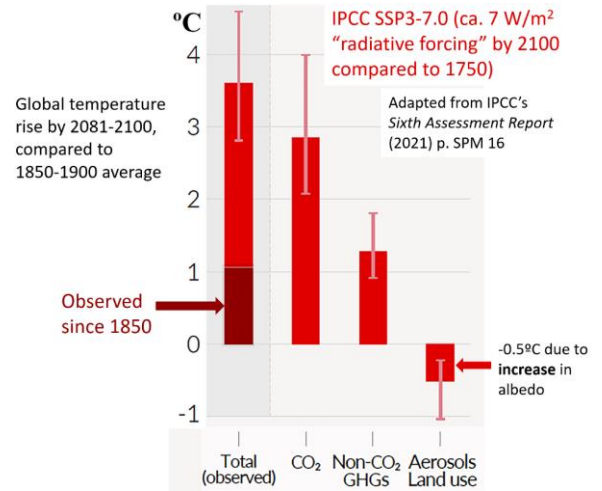
Basic Climate Physics #8

One fact at a time

This short essay is the eighth in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

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The Adiabatic Lapse Rate

Occasionally, I encounter climate skeptics who take the view that there is no such thing as the greenhouse effect; the lapse rate explains why the surface is hotter that the earth as a whole. I have also encountered the argument that the surface is warmer than the air at high elevation because of pressure. I assume that the same is true of many readers of this essay, and herein will discuss the counterarguments that you can use.

If a kilogram of air descends, it warms up by compressional heating. If a kg of air rises, it cools by expansion. For this reason, dry air is cooler by 9.8ºC for every km of altitude, up to about 10 km (roughly the peak of Mt. Everest). For humid air, the rate is lower, but is of no concern to us here. Readers who are interested in the details can find them on Wikipedia and other places.

The rate of change with altitude is called the *lapse rate*, and because the derivation involves no exchange of heat between our little kg of air with the environment, the rate is often called the *adiabatic lapse rate*.

Heat in = Heat Out

Spectra

As geothermal heating is negligible on the global scale, the only source of heat for the Earth is the sun, and the only way for the Earth to shed heat is through infrared (IR) that goes into space. At equilibrium (by definition) the two quantities are equal. Averaged over the sphere, we have $I_{out} = I_{in} = \frac{I_{sun}}{4}(1-\alpha)$, where α is the albedo (for the earth, presently $\alpha = 0.3$.

At our orbit, the spectral nature of sunlight is the blackbody curve characteristic of the sun's surface temperature. Similarly, the spectral nature of IR from the surface is the blackbody curve characteristic of the Earth's surface temperature. By contrast, the spectral nature of the IR radiated to space from the top of the atmosphere is a very jagged spectrum

To put it bluntly, but fairly, it is physically impossible for a temperature gradient (such as the lapse rate) to convert this kind of spectrum (radiation from the surface)

into this kind of spectrum
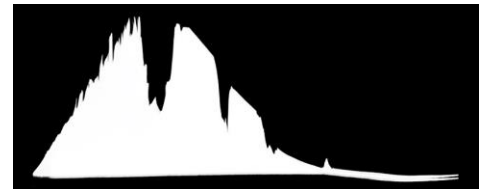
that goes into space.

The Lapse RATE

A rate tells how fast some variable *y* changes with another variable *x*. However, the rate does not tell you what the value is. For example, knowing that a car is moving at 100 km/hour does not tell you where the car is or how long it will take to get to Chicago.

Similarly, the lapse rate tells you how much the temperature changes as you rise vertically but does not tell you what the surface temperature is or what the temperature is at the top of the atmosphere.

Consider a hypothetical Earth that is nothing more than a spherical stone in our orbit that has the same albedo as the Earth. The temperature is calculable from $I_{sun} = 1366$ W/m², using the Stefan-Boltzmann law $I = \sigma T^4$, where

$\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4), and turns out to be 255 K (= –18°C). The radiative flux absorbed and emitted is 239 W/m^2.

Now imagine the Earth with the same albedo but with an atmosphere composed of N$_2$ and O$_2$, both of which are transparent to both visible light and to IR. The same calculation as that in the previous paragraph would apply. The surface absorbs and must radiate 239 W/m^2, and its temperature would be 255K. But now, since there is an atmosphere, there must surely be a lapse rate. Simply put, the temperature would drop from 255 K by 9.8°C for every km of altitude, just as on our present globe. The outer reaches of the atmosphere would be very cold indeed, but in an astronomically meaningless way. That is, if you were about 10 km up from the surface, your thermometer would say 155 K, but since the atmosphere neither absorbs nor radiates IR, nobody would notice but you.

Where the Lapse Rate Does Not Apply

For at least 60 years, scientists have investigated the atmosphere from the ground up. They have developed what is called the *Standard Atmosphere*, a graph of temperature versus altitude. The graph can be found many places on the internet, such as the one at the right from https://www.eoas.ubc.ca/courses/atsc113/flying/met_con cepts/03-met_concepts/03a-std_atmos/index.html.

The lapse rate idea works at altitudes up to about 10 km, but obviously cannot explain the *increase* in temperature from about 20 km to 45 km, or the other peculiarities.

Final Note

Another common misconception is that the atmospheric pressure heats the lower atmosphere, and that is why the surface is warm.

At the grade-school science level, work is defined as force multiplied by the distance through which it is applied. The three-dimensional version is that work is done on a gas when outside pressure moves the surface inward, decreasing the volume. The work done—pressure times the change in volume—becomes heat. That is, when you pump up your bicycle tires, you push air into a smaller volume, and the air warms up a bit. As soon as you quit, the air begins to cool down to ambient temperature.

The pressure inside an oxygen tank is typically about 20 times sea-level atmospheric pressure. That high pressure does not make the tank hot.

Conclusion

The greenhouse effect is real. You cannot explain the IR spectrum to space without it. (But that doesn't mean that we are facing a climate catastrophe!)

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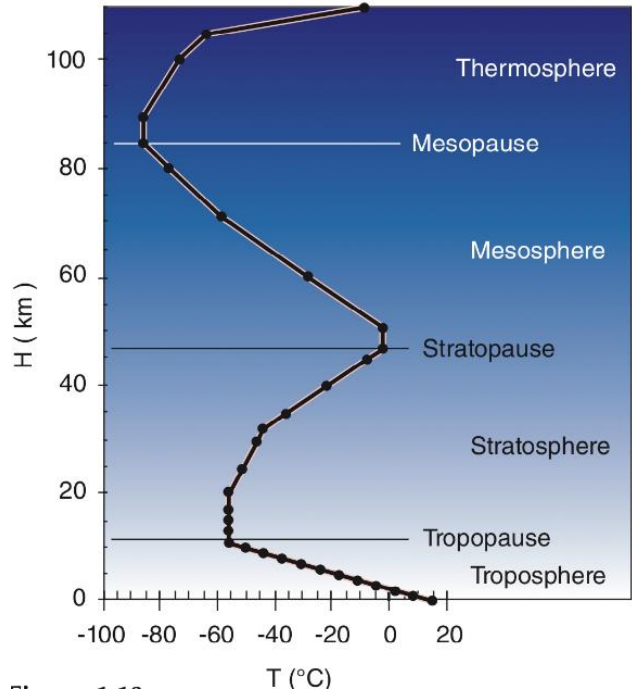
Basic Climate Physics #9

One fact at a time

This short essay is the ninth in a short series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

Feedback

The term *feedback* was probably introduced by electrical engineers, but the term has been used in other fields ranging from control theory to psychology. For example, "That dress looks good on you" is regarded as positive feedback, and "You smell bad" is regarded as negative feedback.

The original scientific meaning, to which we will adhere, is that positive feedback is regenerative feedback: more begets more, rather like compound interest. By contrast, negative feedback is corrective feedback: if you see that your car is too far to the left of your lane, you nudge the steering wheel to the right.

Feedback systems abound in engineering. For example, James Watt applied the principle to the steam engine to keep it running at a (nearly) constant RPM regardless of load. If the engine sped up, flyballs would swing out further from the axis, and a lever mechanism would reduce the amount of steam into the engine. A very similar mechanism is found on small gasoline engines (on lawnmowers and the like), most of them relying on the breeze from the cooling fan as a measure of RPM.

The power steering mechanism on cars works in a similar way. You turn the steering wheel, establishing a "set point." A hydraulic system turns the wheel to an amount determined by the set point, and a negative feedback system keeps it from turning the wheels either too little or too much. (A positive feedback system would immediately turn the wheels as far as they could go, given the slightest nudge of the steering wheel.)

Cruise control works in a similar way. You accelerate up to your desired speed, and then press a button to establish the set point. A signal from the speedometer is compared to the set point. If your car speed varies up (as when you are going uphill or downhill) the system adjusts the fuel and air to the engine.

Over geologic history the surface temperature has varied only plus of minus about 3% (~10K out of 300 K), so it is obvious that the climate is controlled by *negative* feedback.

Feedback in climate models

Climate scientists all (we hope!) recognize that—by itself—CO_2 cannot possibly change the surface temperature very much, even if we double the concentration. If the amount of CO_2 doubles, the "radiative forcing ΔF" (that is, a small change in the greenhouse effect G) would be 3.7 W/m^2. *By itself*, that "radiative forcing" would raise the surface temperature by a trivial 0.68ºC.
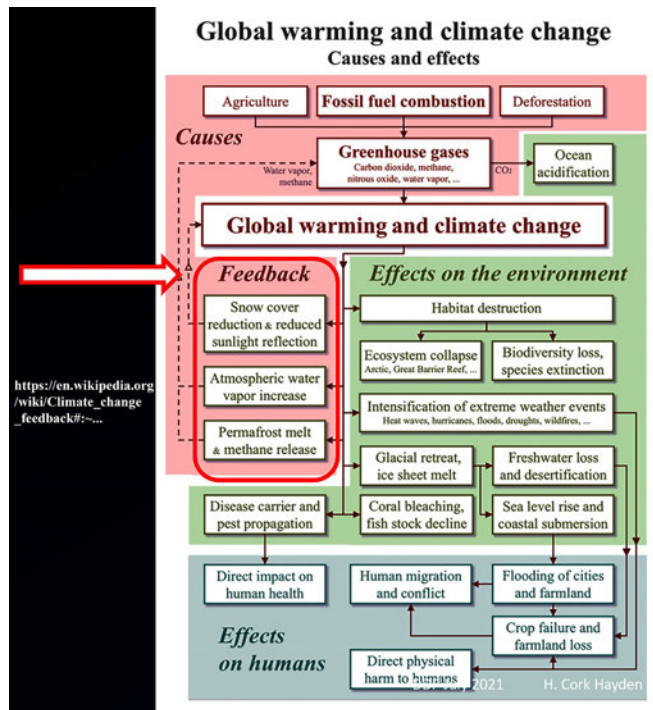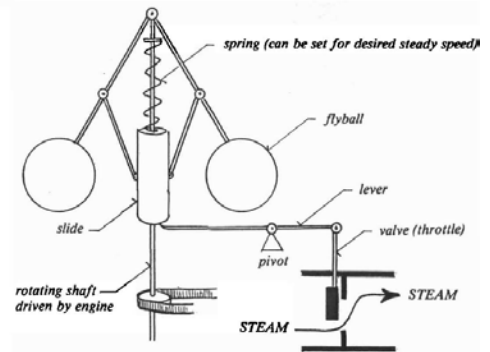
IPCC introduces three positive feedback mechanisms into their models. That increase in CO_2 (1) melts snow and ice, thereby reflecting less sunlight to space; (2) increases the H_2O content of the air, thereby increasing the "radiative forcing" and (3) melts permafrost, thereby increasing the amount of methane (CH_4), a GHG.

CO_2, however, does none of those things. Heat does. You can see from the diagram that that the red line from "Global warming and climate change" points into those three feedback mechanisms. The upshot of the argument is that heat begets more heat.

Now, we will look at IPCC's numbers for a doubling of atmospheric CO_2 concentration:

1. The "radiative forcing ΔF (i.e., an incremental change to the greenhouse effect of 159 W/m^2) will be 3.71 W/m^2.
2. The most probable temperature rise caused by that ΔF will be 3ºC.
   If the surface temperature rises by 3ºC, the surface—by the Stefan-Boltzmann law—radiate 16.4 *more* W/m^2 than at present.

So, the IPCC is saying that 3.71 W/m^2 of heating begets 16.4 W/m^2 of heating. Heat produces 4.4 times as much heat. That's positive feedback for you, and there is no end in sight. One unit of heat begets 4.4 units of heat, and each of the 4.4 units of heat begets 4.4 more units of heat, … without end. To repeat the obvious, CO_2 does not cause the alleged positive feedback mechanisms; heat does. *Any* heat from *any cause* does. So why isn't the planet boiling?

Climate models have neither found a way to account for all the IR (especially the increase due to temperature rise) nor identified the negative feedback mechanisms that ultimately control the climate.

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Basic Climate Physics #10

One fact at a time

This short essay is the tenth in a series about basic (meaning all-inclusive) physics that pertains to the subject of climate.

Bear in mind that my purpose is not to engage in details about wind, rain, snow, storms, historical climatology, Milankovitch cycles, or any of the common topics discussed about climate. What I will discuss is some simple physics.

The Absence of Stefan-Boltzmann

The Stefan-Boltzmann radiation law says that the radiation emitted out through a small hole in a cavity, summed up over the entire spectrum, is equal to $\sigma T^4 = 5.67 \times 10^{-8}\ \dfrac{\text{W}}{\text{m}^2\text{K}^4} \bullet T^4$, where T is the Kelvin temperature. The equation has been around since 1884, and put on a solid theoretical foundation by Max Planck in 1900. Curiously, it also applies to solids as diverse as stars, hot pokers, the surface of the earth, including the oceans and the background radiation of the universe. It is the principle upon which non-contact thermometers work.

One would therefore expect to see reference to the Stefan-Boltzmann radiation law, and the Planck curve in every IPCC report. A search of IPCC *Assessment Reports* reveals that not a single one had the words *Stefan* or *Boltzmann* until *AR6*, (published in **Do Not Cite, Quote or Distribute** form) in 2021. The number 5.67 appears nowhere except for some table entries that have nothing to do with the Stefan-Boltzmann constant. The name *Planck* occurs only in reference to the Max-Planck Institute in the first four *Assessment Reports*. In *AR5* (2014), we are introduced to the jargon *Planck Response* (to be discussed) but nowhere—repeat **NOWHERE**—is there any mention that the Stefan-Boltzmann law always applies to the surface. Nor, more importantly, is the law actually applied to the model-predicted surface temperatures.
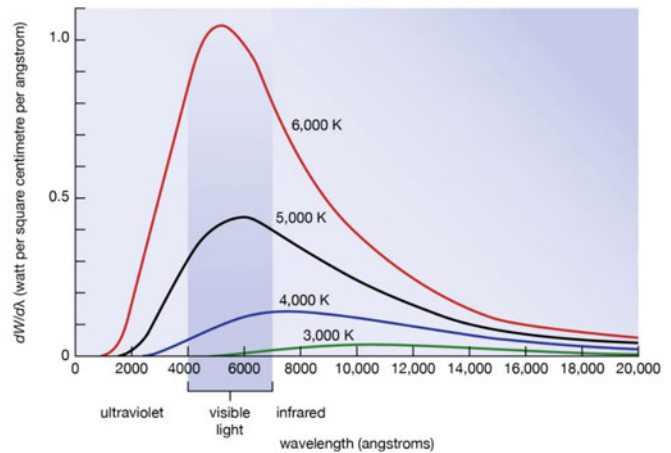
The Planck Response (a.k.a. Planck Feedback)

Look up *Planck Response* on the internet and you find this line repeated *ad nauseum*: "The Planck feedback is the most basic and universal climate feedback, and is present in every climate model. It is simply an expression of the fact that a warm planet radiates more to space than a cold planet." In Lesson #3, we proved that statement false with two examples. (1) The earth with the same albedo but with either the presence or absence of the greenhouse effect (*i.e.,* warmer of colder) emits exactly the same IR to outer space. (2) Venus, with lead-melting surface temperature emits less IR to space than does the earth.

The Planck Response, however, does have some validity. Imagine that somebody sprinkles the right kind of Pixie Dust all over the earth so that the surface warms up. It will radiate more IR and set up an imbalance so that the heat emitted to space (ca. 60% of the surface radiation) will exceed the absorbed solar heat ($I_{\text{out}} > I_{\text{in}}$). The imbalance will continue (and diminish) until the earth cools down to the condition before the Pixie

dust was applied. This is indeed a negative feedback mechanism that tends to hold the surface temperature constant, but it most assuredly does not determine what that temperature is. In particular, it is of no use in calculating the *Equilibrium* Climate Sensitivity (*ECS*, the temperature rise due to CO_2 doubling when $I_{out} = I_{in}$).

More Greenhouse Effect!

If the greenhouse effect increases, such as by increasing atmospheric CO_2 or H_2O, then the IR emission to outer space is decreased. That imbalance ($I_{out} < I_{in}$) warms the surface until the equality between incoming solar heat and outgoing heat radiation is re-established. (Climate modelers take note: **During this time, the warming planet radiates less IR to space than when it was cooler.**) In this realistic case, the increase in the greenhouse effect occurs before the temperature increase, unlike the Pixie-Dust scenario. It is important to remember that the sole source of heat to the earth is sunlight.

Importantly, when the Planetary Heat Balance is restored—that is, when $I_{out} = I_{in} = (I_{sun}/4)(1-\alpha)$—*the additional greenhouse effect ("radiative forcing") must equal the additional surface radiation* unless there is a change in either I_{sun} or albedo α. Recall the Climate Constraint Equation from Lesson #4:

$$G = \sigma T_{surf}^4 - \frac{I_{sun}}{4}(1-\alpha)$$

If the greenhouse effect G increases by (say) 2 W/m² and sunlight and albedo remain constant, then the surface radiation σT_{surf}^4 must increase by the same 2 W/m², and that fact tells us exactly what the temperature rise would be: 0.36ºC for this numerical example.

Asking the Wrong Question

Suppose we have a warehouse containing all kinds of stuff, and that the warehouse is perfectly insulated. Let us ask how much the temperature of the warehouse would rise if we added a certain amount of heat to it. We could calculate the temperature rise if we knew the masses and heat capacities of everything within the warehouse.

Now ask what the temperature rise of the earth would be if we added a certain heat flux in so-many watts per square meter all over the planet. The heat flux (I_{add}) would have entirely different effects on a square meter of ocean, a square meter of desert, a square meter of a puddle, a square meter of rock or a square meter of grass. Presumably with an encyclopedic knowledge of the materials on every square meter of the surface of our planet, we could use a supercomputer to figure it out, but it is fundamentally a fool's errand.

Solution: Ask an Answerable Question

Turn that unanswerable question around and ask: "If the temperature rises by some amount (ΔT), how much more heat flux (ΔI) does it radiate? The Stefan-Boltzmann law provides the unambiguous answer, and does so with a slide rule instead of a supercomputer. (N.B.: If you include emissivities, the numbers change a little, but not enough to balance the Climate Constraint Equation in Lesson 4.)

IPCC's goal (aside from frightening the public) is to determine the *ECS*, the Equilibrium Climate Sensitivity, which is the surface temperature rise (ΔT_{surf}) due to a doubling of CO_2 concentration. They are free to speculate, of course, but they are intellectually obligated to see whether their *ECS* makes sense. All they have to do is to apply the Stefan-Boltzmann law to their predicted temperature rise.

If they do so, they will find out that 16.4 W/m² (for a 3ºC) rise in radiative flux is violently in contradiction to the 3.71 W/m² of "radiative forcing" that their models say causes that 3ºC temperature rise. They are free to come up with an explanation, but they first have to apply the Stefan-Boltzmann law to their *ECS*. Maybe in a few more decades, IPCC will make this discovery.

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