Understanding the Thermodynamic Atmosphere Effect

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Introduction

This article began as a brief two-page summary of the theoretical development of the "Greenhouse Effect". After having several discussions with colleagues, it became apparent that its theoretical basis was not widely understood, even though the theory appeared to be believed in implicitly. In a scientific institution it is generally expected that individuals understand the theories they support and believe in, rather than simply being aware of them and believing in them. Therefore it was curious that there seemed to be so little academic understanding of the theory of the Greenhouse Effect, as opposed to simple awareness of it.

It should be pointed out immediately that the "Greenhouse Effect" is indeed a theory - it is not a benign empirical fact, such as the existence of the Sun, for example. As a theory it has a scientific development which is open to inspection and review. It is extremely curious, from a scientific standpoint, that the word "theory" is almost never associated with the term "Greenhouse Effect" in public and academic circles. Undoubtedly, this fact is related to why even academics are unfamiliar with the theoretical development, let alone the general public's awareness of the theory. Therefore from this point on, the "Greenhouse Effect" will be referred to as the "Greenhouse Theory", indicative of the fact that it is a proposition which needs to be supported by observation and which also needs to agree with other well-established laws of physics. This is analogous to the theory of gravity: just like the atmosphere, no one questions that gravity exists, obviously. What we do question is the theory that describes how it works, and just like Einstein's theory of gravity which breaks down and fails under certain conditions, and isn't compatible with some other branches of physics, we can examine if the Greenhouse Theory also breaks down and fails under the conditions it is supposed to describe. This distinction needs to be stressed because many scientists, who really should know better, will make the claim that the effect of the Greenhouse Theory is a "scientific fact", when in reality a scientist should understand that there is no such thing as a scientific fact, but only scientific theories. These are created with the intention to explain or describe the workings and behaviour of otherwise benign empirical data. For example, again, it goes without question that the Earth has an atmosphere, that the weather changes, and that some force pulls things down to the ground; these are facts of reality, and there is absolutely no need to qualify them with the adjective "scientific". No one questions these things. These facts belong to and are acknowledged by everyone everywhere, independent of science. What scientists attempt to do is create theories which can describe the way these facts of reality work, in a logical way, and in a way consistent with other scientific theories. For example, you may often witness a person insinuate that, if you question the theory of gravity, then you should test it by jumping out a window. This is an extremely anti-scientific thing to say, because indeed, scientists question the theory of gravity one-hundred percent! We don't question that gravity exists, but we do question the scientific theory which describes how it works. And so what we are similarly concerned with here is questioning the Theory of the Greenhouse Effect.

The Greenhouse Theory is the proposition that the atmosphere warms the surface of the Earth to a temperature warmer than it would otherwise be without an atmosphere, *via a process* called "back-scattered infrared radiative transfer". This is just a fancy way of describing the idea that greenhouse gases act like a blanket around the Earth which traps infrared radiation, with the radiation causing it to be warmer than it otherwise would be, and this is supposed to be loosely analogous to how a botanist's greenhouse works. We will examine the proposition of the Greenhouse Theory and see if it is a theory which satisfactorily can explain our observations of the temperature of the surface of the Earth.

The word "radiative" in "radiative transfer" means "of or pertaining to light"; "transfer" is referring to transfer of energy. So radiative transfer means the transfer of energy by light. In this article the word radiative will sometimes be replaced with the word "radiation", but the type of radiation it will be referring to is always "radiative" radiation, again simply meaning light. It is not the type of radiation you would associate with nuclear radioactivity, for example. In physics, light is also called radiation because it "radiates energy away" from its source, be it light-energy from a match, or a star.

The reason why it is important to examine the Greenhouse Theory is because it fundamentally underpins the concern over "global warming", sometimes called "anthropogenic (i.e.

man-made) climate change". These two terms are generally used interchangeably, but are somewhat mutually ambiguous. Anthropogenic climate change can mean any type of change in the climate, be it warming, cooling, more rain, less rain, etc, caused by humans for any reason. Of course, natural climate change has been ongoing at all times throughout Earth's history, and so anthropogenic climate change needs to be distinguished from this. In fact the only constant of climate is that it is constantly changing, for there have been no identifiable periods of climate stasis in Earth's geologic history.

Anthropogenic global warming, on the other hand, means a general warming of the atmosphere theorized to be due to human emission of carbon dioxide (CO_2), which is then theorized to cause a strengthening of the effect of the Greenhouse Theory, which is what actually causes said warming. It is this latter definition which is more fundamental and which directly relates to the Greenhouse Theory, because atmospheric warming via CO_2 can be theorized to lead to various changes in the climate, such as precipitation changes, etc. And it is also possible that small-scale local cooling can take place, even though the average trend of the entire atmosphere would still be towards general warming. Therefore "anthropogenic climate change" falls under the theory of global warming caused by anthropogenic emission of CO_2 and the effect of the Greenhouse Theory. To be perfectly clear, we call it "anthropogenic" global warming (AGW) in order to distinguish it from natural warming, for example from natural changes in the brightness of the Sun, and from natural emission of CO_2 from the biosphere (all life, such as plants, animals and, bacteria) and lithosphere (all geologic activity, such as volcanoes, weathering of rocks such as limestone, the oceans, etc). So Anthropogenic Global Warming caused by anthropogenic emission of CO_2 depends upon the Greenhouse Theory to actually create said anthropogenic warming. And this is distinguished from Natural Global Warming (NGW) which could be theoretically caused by natural emission of CO_2 which would also depend upon the Greenhouse Theory to actually create said natural warming. In other words, the Greenhouse Theory states that an increase of atmospheric CO_2 (or any other "greenhouse" gas, but CO_2 is the one we're most concerned with), be it human or naturally sourced, should cause global atmospheric warming on average via back-scattered infrared radiation, although there may be small-scale local cooling in some locations also. So there are two parts in the analysis of the Greenhouse Theory: Does back-scattered infrared radiative transfer act like a blanket upon, and explain the temperature of, the surface of the Earth, analogous to the way a greenhouse building works; and do changes in atmospheric CO_2 drive significant changes in atmospheric temperature via this type of radiative Greenhouse Theory?

In order to answer these questions we must go through the physics and mathematical development of some basic facts about the way the Sun and the Earth work together in exchanging radiation. We are going to have to look at some mathematics in the upcoming section, but I want to stress one very important thing: I do not require the reader of this article to fully understand or follow along with the development of the math equations. When I read a scientific paper that has lots of math in it, usually I can just skip over the math parts and keep on reading the text to see what the point of it all is. Unless it is a scientific paper that is specifically about the development of some new equations that someone isn't sure of, it is usually sufficient simply to acknowledge that the equation has been written down and showed to you, but you are not required to work it out for yourself. You just have to keep reading along to find out what the point is. The reason why I'm making this point and talking to the reader in the first person here, is because I realize that not everybody reading this has a degree in physics or likes mathematics, and so I don't want them to stop reading along when I start discussing them. The physics involved here is what you would find in current senior-year high-school math classrooms, and first-year undergraduate physics at universities. If it's been decades since you did any math, or physics is your most hated class in school, don't worry about it! Just read along and I'll try to describe what's happening clearly enough so that those who are interested can also work it out for themselves.

One concept needs to be introduced before we continue with some math, which is called a "blackbody". In physics, a blackbody is an extremely important conceptual tool because the behaviour of a blackbody relates to fundamental concepts in physics, such as the Laws of Thermodynamics. A blackbody is simply exactly what it sounds like: an object which is completely black. The reason why it is black is because it absorbs 100% of all the light that strikes it, and doesn't reflect any of it back. Therefore it appears black! This is one part of the "behaviour" we refer to when discussing blackbodies: the behaviour that it has when struck by light. And the behaviour is that it absorbs it all. It should be pointed out that in the real world, most objects will reflect some of the incident light and absorb only the rest. But even in this case many objects can still be very closely approximated by a theoretical blackbody, and you do this by factoring out the amount of radiation lost to reflection. For example, if 30% of the light is reflected, then 70% is absorbed and you can take account for this in the math.

When a blackbody absorbs the energy from light and there are no other heat or light sources around to warm it, then it will warm up to whatever temperature is possible given the amount of energy coming in from the light being absorbed. If the source of light is constant, meaning it shines with the same unchanging brightness all the time, then the blackbody absorbing that light will warm up to some maximum temperature corresponding to the energy in the light, and then warm up no further. When this state is reached it is called "radiative thermal equilibrium", which means that the object has reached a stable and constant temperature equilibrated with the amount of radiation it is absorbing from the source of light. This is distinct from regular "thermal equilibrium", which is when two objects which are in physical contact eventually come to the same temperature, if they started out at different temperatures. In radiative thermal equilibrium, the object absorbing the light will not come to the same temperature as the source emitting the light, but actually will always be cooler than it because the distance between the two objects reduces the energy flux density of the radiation from the source.

This leads us to the second part of the behaviour of a blackbody which makes them so great. When a blackbody has reached thermal equilibrium, it can no longer absorb more light for heating and therefore has to re-emit just as much light-energy as it is absorbing. Because the blackbody can't just reflect the light, it has to re-emit it as thermal radiation. The spectrum of this re-emitted light follows a very well known equation called the Planck Blackbody Radiation Law, after the German physicist Max Planck who helped discover it in the early 1900's. This law allows us to calculate the total amount of energy in a blackbody spectrum, and what the temperature the object actually needs to be at in order to emit that amount of energy. We can determine exactly what the equilibrium temperatures must be. For a real-world object that actually reflects some light but absorbs the rest of the light, when we factor this is into the equations we find that the object still closely approximates the ideal blackbody, and this is of course confirmed by observation. We can therefore calculate the "effective" temperature the object would need to have if it were a perfect blackbody emitting that amount of radiation.

So strictly speaking, although the blackbody absorbs all the light that strikes it, it wouldn't actually appear perfectly black at all wavelengths because the thermal energy it re-emits is also a form of light. But it appears black because this re-emitted light is of a much lower energy than the light being absorbed. For example if the object absorbs visible light, then it will re-emit infrared light which we can't see, and therefore it still appears black. The object would need to heat up to some very high temperature indeed for it to re-emit visible light; a red-hot oven element, for example, can approach 1000^0C (but it heats up due to the electricity being run through it). And as mentioned earlier, in the real world many objects which you wouldn't necessarily expect to behave like blackbodies, also act like blackbodies. Basically, everything tries to act like a blackbody as best as their physical conditions allow for. And so even entire stars like the Sun emit radiation very close to the way a blackbody does, according with the Planck Blackbody Radiation Law. You can therefore understand why the blackbody is such an important conceptual tool in physics. Rarely do you find an actual *perfect* blackbody in nature; but everywhere you look you find things acting very similar to one. As amazing as this sounds, the only thing that really does seem to perfectly resemble a blackbody is the entire universe itself! And probably Black Holes, but that's an entirely different discussion.

Lastly, there is one fundamental law of physics that relates to blackbody emission of thermal energy: it is absolutely fundamentally impossible for a blackbody to further warm itself up by its own radiation. This is actually true for *all* objects, but we'll just keep referring to blackbodies here since that's what the subject is about. For example, imagine a blackbody which is absorbing energy from some hot source of light like a light-bulb, and it has warmed up as much as it can and has reached radiative thermal equilibrium. The blackbody will then be re-emitting just as much thermal infrared energy as the light energy it is absorbing. However, because the blackbody doesn't warm up to a temperature as hot as the source of light, its re-emitted infrared light is from a lower temperature and thus of a lower energy compared to the incoming light that it is absorbing. Now here's the clincher: imagine that you take a mirror which reflects infrared light, and you reflect some of the infrared light the blackbody is emitting back onto itself. What then happens to the temperature of the blackbody? One *might* think that, because the blackbody is now absorbing more light, even if it is its own infrared light, then it should warm up. But in fact it does *not* warm up; it's temperature remains exactly the same. The reason why is very simple to understand but extremely important to physics: the blackbody is already in radiative thermal equilibrium with a *hotter* source of energy, the higher radiative energy spectrum light from the light-bulb. You cannot make something warmer by introducing to it something colder, or even the same temperature! You can only make something warmer, with something that is warmer! This reality is central to the Laws of Thermodynamics, and is so fundamental to modern physics it cannot be expressed strongly enough.

To make the idea more intuitive, imagine a simple ice-cube. Even though an ice-cube is at zero degrees Celsius, it is still 273 Kelvin degrees above absolute zero and therefore has quite a bit of thermal energy inside it, which it does radiate away as thermal infrared energy. Of course, we don't sense this radiation because we're warmer than the ice-cube (hopefully!), and we don't see it because our eyes aren't sensitive to that low frequency of light radiation. Could you then simply bring in another ice-cube which is also at 0^0C and of course also radiating its own thermal energy at that temperature, and thereby heat up the first ice-cube by placing this second one near it? Or could you heat up the first ice-cube by placing it in a freezer at -10^0C? In both cases, there's lots of thermal energy from the secondary sources which falls on the first ice-cube, so shouldn't this energy "go into it" and warm it up? Of course not! You could only heat up the first ice-cube by introducing it to something warmer than it, like the palm of your hand, or a glass of water at 1^0C, or the radiation from the Sun. Or imagine the example of a burning candle: could you use a mirror to shine the candle-light back onto the flame, and thereby make the flame burn hotter? Such conjecture is not the way reality works, and remember, these concepts are true for any object, not just blackbodies. The main point is: heat naturally always flows from hot to cold, whether through conduction, convection or radiation, and most importantly, a body cannot raise its own temperature even if its own radiation was to flow back into itself..

The Radiative Equilibrium Temperature of the Earth with the Sun

We'll now get into some physics and discover that we can quite accurately predict the radiative temperature of the Earth given just a small spattering of the laws of physics. In the equations that appear below, there will always be some letters in brackets (ABC) placed directly to the right of the equations. These letters indicate the units of the parameter which the equation represents. For example, "W" means Watts, "m" means meters, and (W/m^2) would mean Watts per square meter. These are the same type of Watts you look for when purchasing 100 Watt light bulbs, and in physics even the brightness of the Sun in measured in these units (by the way, the Sun's power output is about 385 million billion billion Watts!). They're included to help keep track of what kind of physical process is being described.

The surface brightness of an object is called its flux (f), and it is measured in units of W/m^2. The Stefan-Boltzmann law comes out of an analysis of blackbody spectrums, and it states that an object which radiates like a blackbody has a surface brightness which is proportional to the object's temperature ("T" in degrees Kelvin) to the fourth power, as shown here:

$$f = \sigma T^4 \quad (W/m^2) \qquad \{1\}$$

The proportionality factor 'σ' is called the 'Stefan-Boltzmann constant', and has a value of 5.67×10^{-8} ($W/m^2/K^4$).

The Sun ($\odot$ is the astronomical symbol for the Sun) emits radiation in a manner very similar to that of a blackbody. We know the blackbody-equivalent, or "effective", solar temperature ($T_\odot$) from observation of its spectrum. Therefore we can calculate the total power output, called Luminosity, of the sun by using the above equation and multiplying it by the solar surface area $(A_{surf_\odot})$, which obviously is spherical. Thus:

$$\begin{aligned} L_\odot &= f \cdot A_{surf_\odot} \\ &= \sigma T_\odot^4 4\pi R_\odot^2 \quad (W) \end{aligned} \tag{2}$$

This is the total power emitted by the entire surface of the Sun. To get the solar flux at any distance (d) from the Sun, we must map the luminosity from the spherical surface of the Sun onto a larger sphere whose radius is equal to the distance (d) which is in question. Using the distance of the earth as an example ($\oplus$ is the astronomical symbol for the Earth), and dividing by the area of the larger sphere $(4\pi d_\oplus^2)$, we get:

$$\begin{aligned} F_\odot &= \frac{L_\odot}{4\pi d_\oplus^2} \\ &= \frac{\sigma T_\odot^4 \cancel{4}\cancel{\pi} R_\odot^2}{\cancel{4}\cancel{\pi} d_\oplus^2} \\ &= \sigma T_\odot^4 \frac{R_\odot^2}{d_\oplus^2} \quad (W/m^2) \end{aligned} \tag{3}$$

Note that the spherical areal projection factor of 4π cancels out because we're simply mapping one smaller sphere ($4\pi R_\odot^2$) onto another larger sphere ($4\pi d_\oplus^2$). This is the solar flux on the inside of a sphere centered about the Sun, which has a radius equal to Earth's distance from the Sun. In other words, it is the intensity of solar energy which reaches the earth.

We can now determine the total solar power intercepted by earth. Simply take the solar flux at the distance of the Earth which we just calculated, and multiply it by the cross-sectional area of the earth, which is a disk of earth's radius $(\pi R_\oplus^2)$:

$$\begin{aligned} L_{\odot_{\text{int.}}} &= F_\odot \cdot \pi R_\oplus^2 \\ &= \sigma T_\odot^4 \frac{R_\odot^2}{d_\oplus^2} \pi R_\oplus^2 \quad (W) \end{aligned} \tag{4}$$

However, not all of the energy intercepted by the Earth is actually absorbed by the Earth, because some of the sunlight is reflected straight away back into outer-space. This type of direct reflection is what allows us to see any planets or even the ground at all! The ability of a surface to reflect incident light radiation is called its albedo (α), which is a unitless multiplicative factor which ranges from 0 to 1 (0% to 100%), 0 being no reflection at all and 1 being full reflection. All substances generally have their own unique albedo and for the planet Earth the average value is $\alpha_{\oplus} = 0.3$, which means the Earth, including its atmosphere, reflects 30% of incident sunlight, but absorbs the other 70% in the atmosphere and on the ground. Therefore, if we would like to know how much solar power the Earth and its atmosphere actually absorbs and causes them to warm, we must multiply into the above equation the factor of 70%, or $(1-\alpha_{\oplus})$:

$$\begin{aligned} L_{\odot_{abs.}} &= L_{\odot_{\text{int.}}} \cdot \left(1-\alpha_{\oplus}\right) \\ &= \sigma T_{\odot}^{4} \frac{R_{\odot}^{2}}{d_{\oplus}^{2}} \pi R_{\oplus}^{2} \left(1-\alpha_{\oplus}\right) \quad (W) \end{aligned} \qquad \{5\}$$

And so we've finally arrived at a formula which tells us how much solar energy the Earth and its atmosphere absorb, and it's actually not very complicated. This is the starting point for determining how warm the Earth and atmosphere will actually get from radiative heating from the Sun. To determine this temperature we simply postulate that, given that the Sun has been shining on the Earth for thousands, millions, and billions of years, it will have warmed the Earth and its atmosphere as much as it possibly could have by now and will not be warming them any further. This state is called radiative thermal equilibrium. Now it is true that there are constant short-term variations in the brightness of the Sun and in the albedo of the Earth, and locally parts of the Earth are always rotating from day into night, and so the Sun-Earth radiative balance is generally out of local radiative thermal equilibrium over such periods. However, we are simply interested in long term averages, and so therefore we can examine the average values of the brightness of the Sun and albedo of Earth to arrive at an estimate of the average radiative thermal equilibrium temperature, because in the long term these variations smooth out to averages.

It is actually quite simple to determine what this temperature is because the equation we need is one we've already used. First we need to state another law of physics, called Kirchhoff's Law of Thermal Radiation. It states: "At radiative thermal equilibrium, the emissivity of a body equals its absorptivity." In other words, the Earth will give off just as much power in radiation as it absorbs, when it's in radiative thermal equilibrium with the Sun. If it did not do this then it would not be in radiative equilibrium, but we certainly expect it to be so on average in the long run because the Sun has been shining on the Earth for a very long time indeed. And we've already determined a formula for how much radiation the Earth actually absorbs from the Sun (equation {5}), so we're half-way there.

The final piece of this puzzle is to consider that at thermal equilibrium, an object will generally radiate thermal energy with a blackbody spectrum. And we already know exactly how a blackbody radiates, which we saw in equations {1} and {2}. That is, the total power output (Luminosity) of a blackbody is its surface brightness (σT^4, where T is the object's temperature) times its surface area (A_{surf}), or $L = \sigma T^4 \cdot A_{surf}$, which is what we saw in equation {2}. For the Earth, the emitted power is then:

$$L_{\oplus_{emit.}} = \sigma T_{\oplus}^4 \cdot A_{surf_{\oplus}} \quad (W) \tag{6}$$

To complete equation {6} we need to determine the correct surface area to use, and there are three possibilities depending on if we consider the Earth as a radiation emitting disk, a hemisphere, or a sphere:

$$A_{surf_{\oplus}} = \begin{cases} 1\pi R_{\oplus}^2 \\ 2\pi R_{\oplus}^2 \\ 4\pi R_{\oplus}^2 \end{cases} = \pi R_{\oplus}^2 \cdot \begin{cases} 1 \ \ (disk) \\ 2 \ \ (hemisphere) \\ 4 \ \ (sphere) \end{cases} \tag{7}$$

From equation {7} we can see that circular areas always involve the mathematical term of πR^2. However, there is a projection factor "p" of 1, 2, or 4, depending on whether the surface area is from a disk, hemisphere, or sphere. Therefore if we use "p" to denote the projection factor, we get for equation {6}:

$$L_{\oplus_{emit.}} = \sigma T_{\oplus}^4 \pi R_{\oplus}^2 \cdot p \quad (W) \tag{8}$$

And now we have one simple step left. If we would like to know the radiative equilibrium temperature of the Earth, via Kirchhoff's Law we can simply equate the power emitted by the Earth to the total solar power absorbed by the Earth, and then solve for the unknown variable $T_{\oplus}$:

$$L_{\oplus_{emit.}} = L_{\odot_{abs.}}$$

$$\sigma T_{\oplus}^4 \pi R_{\oplus}^2 \cdot p = \sigma T_{\odot}^4 \frac{R_{\odot}^2}{d_{\oplus}^2} \pi R_{\oplus}^2 \left(1 - \alpha_{\oplus}\right)$$

$$T_{\oplus}^4 = \frac{\cancel{\sigma} T_{\odot}^4 \frac{R_{\odot}^2}{d_{\oplus}^2} \cancel{\pi} \cancel{R_{\oplus}^2} \left(1 - \alpha_{\oplus}\right)}{\cancel{\sigma} \cancel{\pi} \cancel{R_{\oplus}^2} \cdot p}$$

$$T_{\oplus} = T_{\odot} \sqrt[4]{\frac{R_{\odot}^2}{d_{\oplus}^2} \frac{(1-\alpha_{\oplus})}{p}} \qquad \{9\}$$

There are some interesting things about this result. First is that it's relatively simple and easy to calculate. Second is that all the parameters in the equation are known or easy enough to determine. And the most important is that the numerical area factor of $\pi R_{\oplus}^2$ actually cancels out, and the only real dependence is upon an objects distance from the Sun and its areal projection factor "p", and so this equation can be used for any circular object as long as you know the projection factor (and its albedo).

For the entire planet Earth as a whole, we must consider that both the sun-facing side of the earth *and* the dark-side of the Earth emit thermal radiation. It is true that only *one* side of the Earth ever collects solar radiation at a time, but it is both sides which re-emit thermal radiation. Therefore on average the Earth and its atmosphere must be treated as a sphere with *p* = 4, if you want the theoretical average temperature of the entire sphere. Utilizing the parameter values here:

$$T_{\odot} = 5778 \quad (K)$$
$$R_{\odot} = 6.96x10^{8} \quad (m)$$
$$d_{\oplus} = 1.496x10^{11} \quad (m)$$
$$\alpha_{\oplus} = 0.3$$

we can calculate that the average radiative equilibrium temperature of the Earth with the Sun is:

$$T_{\oplus} = 255K = -18^{o}C \qquad \{10\}$$

Is this theoretically calculated temperature confirmed by the actual observed radiative temperature of the Earth? We will answer this question definitively in a moment, but first a few points should be discussed.

It is of the utmost importance to understand that this calculated temperature is 1) only an average temperature, and so will *not* be found generally in all places; 2) only the radiative equilibrium temperature of the entire object, and so the rotation of the earth going from daytime (collecting solar energy and emitting thermal energy), to night-time (only emitting thermal energy), will constantly cause local small scale deviations from thermal equilibrium, both hotter and colder; 3) not the average temperature at the actual ground surface at sea level, because most of the Earth's thermally emitted radiation comes from high up in the atmosphere and therefore this is the temperature you find up there.

As an example of some differences we can find, imagine that you have a dime-coin which you've painted to have an albedo equal to the Earth's. You orient the dime so that its face points directly at the sun. This object has a projection factor of p = 1 (a disk), and so the thermal equilibrium temperature of the sun-facing side of the dime is calculated via equation {9} to be 360K, or 87^0C! Well, you could place that dime on the ground when the sun is directly overhead, and then it simply becomes part of the ground and the same equation applies. So when the Sun is directly overhead, the local ground can be approximated as a disk and so it too could attain a temperature of 87^0C.

Local variations in albedo also create differences from the average result. Ocean water is actually very dark and has a very small albedo, going down as small as $\alpha_{ocean} = 0.03$ when the sun is directly overhead. Using this value of albedo and considering the local equilibrium temperature when the Sun is directly over some part of the ocean, the temperature calculates out to 391K or 118^0C! (We'll come back in a few moments to ask why these high temperatures are not actually found at the ground surface of the Earth.)

These types of variations from the average may be thought to present a problem for actually confirming if our calculation for the global radiative average in equation {10} is correct or not. Well, there is actually a very simple solution. Because what we've calculated is the *radiative* equilibrium temperature between the Sun and the Earth, we just need to check what the radiative temperature of the Earth (and its atmosphere) is! And this is done the exact same way as is done for the Sun: we check the spectrum of the emitted radiation by observing it from outer-space. The radiative spectrum of the Sun closely resembles a blackbody spectrum, and so does the Earth's, and because of this we can calculate the effective blackbody temperature required to create the observed spectrum. Now obviously, the day-time and night-time temperatures of the Earth are generally different from each other, and therefore will have different spectrums. However, because it is the average spectrum we want in order to compare to the average temperature we calculated, we just observe the spectrum from all sides of the Earth and simply average the results together.

In yet another amazing confirmation of the power of the Laws of Thermodynamics, blackbody spectrums and Kirchhoff's Law of radiation, the average spectrum of thermal radiation from the Earth (and its atmosphere) indeed resembles a blackbody at **-18^{0}C**! And so the radiative equilibrium temperature of the Earth is measured to be exactly just what we calculated! The Earth is neither warmer nor cooler than it should be under the laws of physics. Such is the power of modern physics and simple mathematics, and it is really quite amazing.

The Temperature of the Ground Surface at Sea Level

Via equations {1} and {3} it can be calculated that a perfect blackbody sphere surrounding the Sun at a radius of one astronomical unit (1 a.u., the distance of the Earth from the Sun) would heat to an equilibrium temperature of 121^0C. This is the maximum temperature any conceivable object could reach from solar radiative heating, and corresponds to the equivalent energy flux density of solar radiation at this distance. The Laws of Thermodynamics tell us that there is no possible natural re-exchange of this radiation which can cause further heating. When the Sun is directly overhead some part of the Earth, the local ground is disk-like and therefore has the potential to warm up to this temperature as well, but local variations in albedo and atmospheric absorption will cause a reduction from this.

Let's consider an example which should be intuitive for most people. Sand can have a range in albedo from slightly under 20% and up to 40%, and for beach sand we'll take the average value of 30%. This is convenient because it's the same value as the average for the entire Earth. On a hot sunny day at the beach, in mid-summer, the Sun is very close to being directly overhead for a few hours around solar-noon. During this time, the Stefan-Boltzmann equation calculates a local equilibrium temperature of 87^0C. We are all familiar with running across the hot sand trying to keep our bare feet from being scalded, but the sand temperature is not nearly 87^0C, and is actually closer to 45^0C - 55^0C. What is the source of the discrepancy here?

In astronomy, the process of measuring the brightness of a star is called photometry. It has been well understood by astronomers for hundreds of years that the brightness of a star is reduced when its light travels from empty outer-space and then into and through the atmosphere down to the ground where the telescope is. Basically we can imagine the atmosphere of the earth acting as a fog, which thereby reduces the brightness from a light source compared to if there was no fog at all. The very first step an astronomer calculates in order to determine the brightness of the star they are measuring is to mathematically apply to the measured brightness data what is called a "photometric correction". There are various observational methods to determine the actual mathematical values for this correction, which we needn't go into here, but after this correction is applied to the data the astronomer is left with what is called the "outside atmosphere" brightness of the star. This atmospheric effect is in fact mathematically identical to how vehicle headlights are reduced in brightness over distance when driving on a foggy night. In astronomy and physics this phenomenon is generally called "atmospheric extinction".

It is often said that Earth's atmosphere is transparent in the visible wavelengths, implying that *all* the visible light from the Sun makes it down to the ground. This simple interpretation is physically inaccurate. Of course, sunlight *is* starlight and so the effects of atmospheric extinction equally apply to it as well. Yellowish wavelengths of light suffer approximately 25% atmospheric extinction when the Sun or a star is directly overhead, with shorter wavelengths suffering more and longer wavelengths suffering less; the weighted average extinction over all wavelengths roughly comes out to 25%, but this can be slightly higher or lower depending on how clear the air is. The amount of extinction is also always increased if the light shines through more atmosphere, which is what happens when the star is not directly overhead. The light then travels through the atmosphere to your location at an angle. Of course, if there are clouds, then hardly any starlight gets through at all.

The net result is that of the total solar radiative energy that strikes the top of the atmosphere, only 75% of it makes it down to the actual ground surface when the Sun is directly overhead. The other 25% of solar power gets lost in the atmosphere via extinction. If we symbolize extinction with the Greek letter epsilon (ε), we can easily modify equation {9} to account for this, and we can then more accurately predict the actual ground-surface radiative equilibrium temperature. We simply incorporate extinction (ε) the exact same way we did for albedo, and the new equation becomes:

$$T_{\oplus} = T_{\odot} \sqrt[4]{\frac{R_{\odot}^2}{d_{\oplus}^2} \frac{(1-\alpha_{\oplus})(1-\varepsilon_{\oplus})}{p}} \qquad \{11\}$$

What does this equation predict for the temperature of beach sand on a nice hot summer day? Using the parameters listed earlier and with $\varepsilon_{\oplus} = 0.25$, the temperature of the sand is calculated to be 62^0C, and this is very close to what we would expect. If the day is really clear and the extinction is reduced, it can be maybe five degrees warmer than this, on the sand. If the albedo is reduced because you're walking on asphalt, well then it gets even hotter! The air which surrounds you on days like these does not get quite this hot, but might usually reach 35^0C. The reason the air doesn't get as hot as the sand, even though it is in contact with it, is because it is continually circulating, with the air that is in contact with the ground instantly rising and thus expanding and cooling, with the cooler air above then falling down to take its place. This rising and expanding of hot air and falling of cool air is called atmospheric "convection". If it weren't for this continuous convective cooling, the air temperature on the beach would grow truly unbearable and they would be the most-avoided places on the planet.

The fraction of solar radiative power which is absorbed directly by the atmosphere (approximately 25% via extinction) doesn't contribute to the ground-air temperature in the above example. There are a couple of reasons for this. The first is that the air only absorbs 25% of the solar energy, versus the 45% that the ground absorbs (after factoring out average albedo). Automatically this tells you that the air will not be warmed, via radiation, as much as the ground. And of course, something which is cool cannot transfer heat to something which is warm, either via conduction or radiation, in accordance with the Laws of Thermodynamics. The second reason is that the atmosphere is a volume, not a surface, and there is therefore much more "material" that needs to be heated up. Or in other words, the solar energy gets spread around to a lot more material in the atmosphere, and therefore gets diluted. A physical surface like the ground gets all the solar energy concentrated directly on the two-dimensional surface, but the atmosphere absorbs the energy within a three-dimensional volume. If you could treat the local atmosphere as a disk which absorbs only 25% of the available incoming radiation from the Sun, then its equilibrium temperature would be about 6^0C. However, this is too simple of an approximation to make for this case because air convection currents off of the ground will transport heat high up into the atmosphere. There would also be radiative heating from the warmer ground and into the cooler atmosphere, but this effect would be completely dominated by the much more efficient physical conduction and convection processes.

What is the total surface area of the Earth, directly underneath the Sun, which can be approximated as a disk? The surface of the Earth is obviously a circular curve, so we can simply specify that we will consider no more than a ten percent deviation from a flat disk in the approximation. Using basic trigonometry we would find that a circular area with a diameter of 5,747km would be 90%, and better, in approximation to a disk, given Earth's radius of 6371km. This equates to a surface area of about thirty-three million square kilometres, which is one-third larger than the entire continent of North America! Now consider this area applied to the Pacific Ocean. If it were cloudless over the area of the disk approximation, then the albedo from the ocean would easily average 5% and the extinction would still be close to 25%. If we also reduce the flux in the Stefan-Boltzmann equation by 10%, we then calculate an equilibrium temperature of at least 80^0C, and as high as 89^0C, for this entirely huge expanse of water! If you incorporate clouds and the average albedo of 30%, then you get at least 54^0C and as much as 62^0C for any general area on the Earth directly underneath the Sun, including land. Of course, for the oceans the solar input energy is not entirely absorbed at the surface of the water, but with the majority within a few dozen meters of the surface, and so it doesn't get this hot. The warmest ocean water is found in the Indian ocean where some parts reach 28^0C. You also have continuous ocean currents which circulate warm tropical water to the poles, and cold polar water to the tropics. The point of all this is to understand that there is an entirely huge surface area of the Earth which is gathering an entirely huge amount of solar energy, and this is even after having correctly factored out the energy loss from extinction. And we can also infer that the only real way to change the amount of heat in the ocean is to change the amount of sunlight which reaches it. This can only happen by a change in the brightness of the Sun itself, or possibly by a very long-term change in atmospheric extinction, because ocean water generally wouldn't be expected to change in albedo. The atmosphere does not transfer heat to the ocean in total, given that the ocean totally dominates the atmosphere both in terms of the amount of energy it is able to absorb from the Sun at any given time due to its low albedo, and the much higher heat capacity of water as compared to air. Heat flow is dominated by evaporative heat-loss from the ocean into the atmosphere during both night and day.

The same analysis can be applied to desert and tropical areas with a good degree of accuracy. As we have seen, using the average albedo of 30% and extinction of 25%, there is more than enough solar input power to warm the surface to a very high temperature. Much of this energy is absorbed into ocean heating, but over land a good deal of it goes into water vapour. Both liquid water and water vapour have extremely high heat capacities, which means that they can hold a great deal of energy without heating very much. Or conversely, once liquid water or water vapour has warmed up, it will hang on to that heat energy for a significant period of time before that heat is radiated away. A very good example of this is in comparison of desert night-time temperatures versus tropical ones. In a desert, the atmospheric water vapour content is extremely low; in a tropical rain forest, it is the highest of anywhere naturally found on Earth. It is this reason that an equatorial desert will drop in temperature by as much as 60^0C from maximum to minimum over the course of a day and night, while a tropical rainforest will only drop in temperature by 5^0C - 10^0C. The rainforest cools down a lot slower than the desert because there is a great deal more water vapour in the air, which is very good at holding onto heat. To be clear, it is incorrect to say that the water vapour "causes heating" of the air at night in the tropics; what is physically correct is to say that the water vapour has a very slow rate of cooling, and therefore keeps warm longer. But you can be assured that, if the Sun never came up again, both the tropical rain forest and the equatorial desert would continue cooling to just a few degrees above absolute zero.

Moving to a larger surface area, the hemisphere of the Earth which is illumined by the Sun has a projection factor of '$p = 2$' in the Stefan-Boltzmann equation. If you apply an average 30% albedo and consider the ground-plus-atmosphere aggregate, and therefore do not also factor out the extinction, then the radiative equilibrium temperature is calculated to be about 30^0C. So the *entire* hemisphere of the Earth which faces the Sun has the potential to warm up to a high temperature, on average! As you move from the equator to the North and South poles, the angle the sunlight makes with the ground grows larger and larger and this reduces the solar energy per square meter, or energy flux density, which then reduces the temperature of radiative equilibrium. A very simple cosine-dependant mathematical model would predict that the temperature at the poles should be near absolute zero, because at ninety angular degrees from solar zenith the ground will not collect any solar radiation at all. Of course, air and ocean currents carry the heat collected from warmer areas and transfer it to the poles, and so they only go down to -40^0C to -50^0C in their coldest winter seasons.

This simple mathematical model based solely on solar energy radiative equilibrium would actually predict that the entire periphery of the hemisphere, the whole circular boundary between daylight and darkness, should be near absolute zero. And given that the dark-side of the Earth doesn't collect any solar radiation at all, the Stefan-Boltzmann equilibrium equation cannot even directly apply. However, equatorial regions going from day to night (or night to day) are still much warmer than the poles, and the reason for this is obvious: the rotation of the Earth essentially "throws" the heat the ocean and ground continually collect in the day-side and over into the night-time side. And even in a desert where the night-time cooling is most rapid due to the lack of local atmospheric water vapour, the rotation of the Earth is fast enough that before it gets too cold, the Sun rises again and re-starts the daily warming process. We will return to this topic of hemispherical heating in our review of the greenhouse theory ahead, because it is very important.

We finally return to considering the Earth as a whole, rather than smaller parts of it. We have seen that, on short time-scales, local areas of the Earth's surface will try to come to thermal equilibrium with the incoming solar energy and will therefore warm up to potentially very high temperatures. It was very important to develop this understanding of why, and from where, the day-time warmth comes from locally, before we finish this segment with a full thermodynamic analysis of the total aggregate average of the entire planet.

As we have discussed, in the long run the incoming solar energy gets distributed around the entire planet. We therefore use a projection factor of 'p = 4' in the Stefan-Boltzmann radiative equilibrium equation in order to calculate what the long-term average theoretical equilibrium temperature of the entire Earth should be. Like the examples we just discussed, the total average equilibrium temperature calculated via the Stefan-Boltzmann equation is what is actually confirmed by observation: a blackbody spectrum at 255K or -18^{0}C. Now, what happens if we try to calculate the long-term ground-surface equilibrium temperature if we factor out the 25% energy lost due to atmospheric extinction? We then calculate a whole-Earth ground-surface temperature of only -45^{0}C. Or, if you apply the 25% of solar energy to direct heating of the atmosphere via extinction, then we calculate an air temperature of only -76^{0}C. These temperatures are not what are actually measured for the long-term averages, and the reason why is very important to understand: It is only in the long-run where you can get an accurate temperature calculation for the *entire* Earth system. In the short term, you can separate out the extinction effects from the atmosphere and very accurately determine the ground-surface day-time temperatures underneath the Sun. But in the long run, all the heat gets spread around as much as it possibly can, and then the ability to thermodynamically distinguish between the atmosphere and the ground disappears. In the long-run, thermodynamics does not care where all the heat gets spread around to. The ground of the Earth plus the atmosphere around it represent an aggregate thermodynamic system, and when you consider the equilibrium temperature of the long-term whole, which is what we do when we just factor out the albedo, then the radiative equilibrium temperature we calculate applies to that whole aggregate system. So when we talk about the long-term equilibrium temperature of the Earth, we are not referring simply to the ground of the Earth, but rather to the entire ground (including sea-surface) plus atmosphere system. The calculated -18^{0}C thermodynamic average applies only to the entire aggregate long-term system, and it is this system we observe when we confirm the equilibrium temperature by measurement of Earth's spectrum from space.

In light of all this, it can be understood that the radiative equilibrium equation we've been using cannot on its own tell us anything about where to actually go and physically locate that equilibrium temperature. All we know is that, somewhere within the aggregate system of ground +

atmosphere, the equilibrium temperature will establish itself in some average location. With an expanded understanding of the Laws of Thermodynamics, however, we can actually get to that answer. But first, of course, we must understand a couple of thermodynamic concepts.

Consider a solid bar of gold which is at a stable temperature of 255K or -18^{0}C. The distribution of the atoms within the gold bar is homogenous, meaning that they are spread evenly throughout the bar and the density is completely even, everywhere within the bar. When we talk about the bar being at -18^{0}C, what this means in terms of thermodynamics is that this is the average, or most common, temperature of the atoms in the bar. If the bar was radiating thermal energy similar to a blackbody, then the spectrum of this radiation would have a peak of maximum intensity which corresponds to -18^{0}C. However, this does not mean that every-single atom in the bar is vibrating with an energy corresponding to -18^{0}C; this is simply the average, or most common, rate of vibration. What really is happening is that there are some atoms which randomly vibrate faster and some which randomly vibrate slower. This corresponds to higher and lower temperatures for those atoms and so therefore, they respectively emit higher and lower frequency thermal radiation. Now, the atoms which spontaneously vibrate faster and slower are completely random in space, time, and identity, and so you cannot ever identify which atoms will vibrate faster and which ones slower. It just randomly happens because with an extremely large number of atoms all vibrating together, some will get bounced faster and some will get bounced slower. It is the faster and slower atoms which emit the thermal radiation on the higher and lower frequency side of the -18^{0}C peak in the blackbody spectrum. Even if you were able to set-up a bar of gold in which every single atom had the exact same rate of vibration and temperature - this is what we would mathematically call a "delta-function distribution" - within milliseconds this distribution would re-sort itself out such that the emission of thermal radiation corresponded to a blackbody spectrum.

Now let's consider the distribution of molecules in the atmosphere. These molecules are not distributed evenly, and in fact become more densely packed together the closer they are to the ground. Obviously we're referring to atmospheric pressure: at the top of the atmosphere there is hardly any gas and the pressure is very low; at the bottom of the atmosphere there is lots of gas and the pressure is very high. At the bottom of the atmosphere is the ground, and this is a solid physical boundary. It's widely known that the higher you go in altitude, the cooler it gets, and so it is the bottom of the atmosphere at the boundary with the ground is where it is warmest. And because in a thermodynamic system you will have some parts of it which are warmer than the average, and some parts which are colder than the average, we can conclude that the most common, average equilibrium temperature should be found somewhere between the ground, which is warmest, and high up in the atmosphere, where it is coldest. The average, most common temperature of -18^{0}C should not be on the ground, nor should it be at the top of the atmosphere; it should be somewhere in between. As an aside, if you go too high up above the Earth the usual laws of ideal gas thermodynamics no longer apply because of interactions with the solar wind and related ionization effects. The temperature in these regions can go into the thousands of degrees. However, because there is so little gas in this uppermost region, the amount of heat that's actually held is negligibly small. Spacecraft fly through this region all the time without any problem. The portion of the atmosphere we are concerned with, in the thermodynamic average equilibrium system, is the lower part which is called the troposphere, and this is where the usual laws of thermodynamics do still apply. The troposphere contains about 90% of the mass of the atmosphere and within an altitude less than around 17km. Above this the gas is just so thin that it hardly contains any total heat at all.

So unlike the example of the gold bar, the gravitational compression of the gas of the atmosphere does qualitatively create a distribution of temperature. In the gold bar we couldn't identify when, where, or which atoms would be the hotter or cooler ones than the average. In the atmosphere however, we can identify where the hotter and cooler ones are: the hottest are at the bottom, the coldest are at the top, on average, weighted for volume and density. The really nice thing about thermodynamics is that you can use the simplest equations to predict the outcome of complex systems, such as we have seen for the thermodynamic equilibrium temperature of Earth's ground + atmosphere system. The calculation perfectly matched the observation. We can do the exact same thing for the distribution of temperature of a gas in a gravitational field.

Let's consider a vertical column of gas, or air, in the atmosphere. In the long-term average, this column of gas will be in thermal equilibrium with the solar input energy, and so will contain a finite and constant total energy. When it has reached this state, the internal energy of the column of gas will be composed of both thermal energy and gravitational potential energy. Thermal energy is the energy from heat, gravitational potential energy is the energy from height above the ground. When it has stabilized to thermal equilibrium, the distribution of temperature will not be uniform, as we have discussed. Even though there is a non-uniform temperature distribution, the column of gas will still be in thermal equilibrium because the non-uniformity simply arises due to the decreasing density of the atmosphere with altitude. The internal energy of an arbitrary small parcel of air in the column can be expressed as a sum of the thermal and potential energies. We can therefore write a mathematical equation which describes this thermodynamic situation, as shown here:

$$U = C_p T + gh \qquad \{12\}$$

In this equation, 'U' is the total energy, 'C_p' is the heat capacity of the gas, 'T' is the temperature of the air parcel, 'g' is the strength of gravity at the Earth's surface, and 'h' is the height of the parcel above the ground surface. At equilibrium, the total energy 'U' will be constant, and so if we differentiate the above equation, we get:

$$dU = 0 = C_p \cdot dT + g \cdot dh \qquad \{13\}$$

We can easily rearrange this equation to tell us the distribution of temperature with height:

$$\frac{dT}{dh} = -\frac{g}{C_p} \quad (K/km) \qquad \{14\}$$

The values of 'g' and 'C_p' are both positive, and so equation {14} tells us that the distribution of the temperature of a gas in a gravitational field, like the atmosphere around the Earth, has a negative slope. This means that the temperature decreases with height above the ground, and this matches exactly what we already expected. The ratio of 'g' over 'C_p' is generally called the "adiabatic lapse rate", and for dry-air would have a value of 9.8K/km (Kelvin per kilometre), but the moist-air average is 6.5K/km. We can solve equation {14} in the form of a simple linear equation, which takes the solution shown here:

$$T = \frac{-g}{C_p}(h - h_0) + T_0 \quad (K) \qquad \{15\}$$

This equation is identical to the simple form of "y = mx+b", which most people should be familiar with. The terms 'h_0' and 'T_0' (pronounced h-naught and T-naught) establish the zero-point of the equation for the altitude and temperature; essentially, we need to find values for 'h_0' and 'T_0' which correspond to each other, and this can be done by observation. We already established a zero point for the temperature (T_0) when we calculated the total average equilibrium temperature of the ground + atmosphere system, at -18^{0}C. Therefore, we simply need to find the average altitude (h_0) corresponding to where this temperature is most commonly found, which is the average surface of radiative equilibrium. This altitude is found at about 5km in height above the ground surface by observation. Therefore equation {15} can be written as:

$$T = -6.5(h - 5) - 18 \quad (^0C) \qquad \{16\}$$

The average temperature in degrees Celsius, at the bottom of the atmosphere at zero height (h = 0) above the ground surface, is therefore calculated to be: **+14.5^{0}C**. This predicted average ground-air temperature is also exactly what is observed! Isn't it just amazing what a proper understanding and application of the Laws of Thermodynamics can do to describe reality around us! If a dry-air lapse rate of 9.8K/km is used in the equation, for example for the air over a desert, then higher local temperatures will result.

The Case of Venus

There is much confusion over the comparison of Earth to that of Venus, in regards to the theory of the greenhouse effect. Many people will make the point of the high surface temperature on Venus as if it is some form of a confirmation of the atmospheric greenhouse idea. This is incorrect. In considering the very high surface temperature of Venus, which is 460^{0}C, we must consider three very enlightening facts.

First, Venus is closer to the Sun, meaning that it obviously receives much stronger solar radiation, and therefore more heat. However, Venus also has a sulphuric acid cloud layer which reflects a very high percentage of the incoming solar radiation, so that it actually has a slightly cooler radiative equilibrium temperature than that of the Earth's. Venus' albedo is equal to 0.67, and its distance is equal to 72.3% of that of Earth, and so its global radiative equilibrium temperature is calculated to be about -25^{0}C, which is just a little cooler than that of the Earth's. And also similar to that of Earth, Venus experiences a maximum heating underneath the Solar zenith of about 80^{0}C, even with its high albedo.

Second, Venus has an *extremely* long day, meaning that it rotates underneath the Sun very, very slowly. Venus' "day" in fact lasts two hundred and forty three (243) Earth days! With such a slow rotation, there is plenty of time for the Sun-facing hemisphere of Venus to collect an extremely large amount of energy to distribute around as heat before it rotates out of view of the Sun, thus sustaining its very thick atmosphere. The thick atmosphere very efficiently circulates the heat collected on the day-side over to the night-side, so that the dark hemisphere of Venus doesn't actually cool down very much as compared to when it is being heated directly by the Sun.

Third, and this is the very important point which ties it all together, Venus' atmosphere is *ninety-two* times more dense at the surface, as compared to the Earth! This degree of pressure is found only at around one-kilometre depth underneath the ocean surface on Earth, where even state-of-the-art, modern nuclear powered attack submarines would be crushed. In fact, similar temperatures and pressures as found on the Earth's surface *are* found in Venus' atmosphere at a height of about fifty-kilometres, and below this the temperature and pressure increases due to compression and adiabatic heating. And this serves as a rough zero-point for determining the ground temperature on Venus via the same adiabatic equation as we used above for the Earth. Venus' atmospheric composition is very different than Earth's, but it's average adiabatic lapse rate is still very similar, at around 9K/km. So if the Venusian atmospheric temperature at 50km altitude is around $+15^0$C, then at 50km in depth at the ground surface, the adiabatic equation derived above would calculate out to around 465^0C, which is really quite close to what Venus' ground temperature actually is.

We can now understand what is meant by the expression "runaway greenhouse effect", when used to describe the situation on Venus. First of all, the temperature on Venus' surface is exactly what it is supposed to be: calling it a "runaway" effect conjures something which isn't supposed to be. Secondly, the ground temperature on Venus is higher than the maximum possible heating as provided by sunlight, whereas on the Earth, the maximum measured ground temperature is much *less* than the maximum possible, given the energy flux density of incoming sunlight. So on Earth, we see that the atmosphere has a net cooling effect, because the average ground temperature is *less* than the maximum temperature the Sun can provide underneath its zenith. But on Venus, the atmosphere there makes the average surface temperature hotter than it could ever get from solar heating, not because of any radiative trapping by the atmosphere, but simply because of its massive adiabatic heating capability. The low density atmosphere of the Earth in fact behaves the opposite way that Venus' very high density atmosphere behaves, in terms of regulating the planetary surface temperature. And so the pseudo "runaway" aspect of Venus merely refers to its very high density and very deep atmosphere, which makes the surface warmer than is possible given the amount of absorbed solar radiation, and this has absolutely nothing to do with trapping unavailable radiation near the surface. This implies that the only real way to increase the temperature on the surface of the Earth via an atmospheric "greenhouse" effect is to increase our atmosphere's density. However, we would be faced with the problem of finding more air, in order to do that! Of course, the amount of change of CO_2 in the atmosphere is negligible in concentration, and its effect on atmospheric pressure is too small to even measure.

Theory of the Greenhouse Effect vs. the Thermodynamic Atmosphere Effect

Now that we've developed a decent understanding of the way the atmosphere behaves according to the accepted Laws of Thermodynamics, we can compare this understanding to the suppositions of the Theory of the Greenhouse Effect.

The greenhouse theory states that the reason the ground is warmer than -18^0C is because the atmosphere, via greenhouse gases like CO_2, re-emits thermal radiation towards the ground and therefore amplifies the heat at the ground from -18^0C up to $+15^0$C.

- Thermodynamics says that no object in the universe can heat itself by its own radiation, nor can heat flow from cold to hot. Thermodynamics explains the ground temperature, on average, as a result of the adiabatic temperature distribution of a gas in a gravitational field, given an average radiative thermal equilibrium which necessarily becomes established in the atmosphere at altitude. This matches what we understand about thermodynamic temperature averages: there has to be some parts of a complex aggregate system which are hotter, and some which are cooler, but most will be at the average. Hotter should be found at the ground, cooler should be found high in the atmosphere. It does not matter that some energy is re-emitted back down to the ground, because it can never be enough energy to heat itself.

The greenhouse theory states that it is Earth's ground surface which should be in equilibrium with the energy from the Sun at -18^0C, but greenhouse gases raise the temperature of the ground above the equilibrium temperature

- Thermodynamics says that it is only the ground surface + atmosphere aggregate system average which should be in equilibrium with the Sun, at an average temperature of -18^0C, and that this temperature will *not* be found specifically at the ground, but well above it in the atmosphere. The average ground temperature will be higher than the average equilibrium temperature with or without greenhouse gases. It is fundamentally incorrect to compare the radiative equilibrium temperature of -18^0C to the ground temperature, because these are not the same physical concepts. The ground temperature is a-priori a different physical metric than the radiative equilibrium temperature, and comparing them is physically incorrect.

The greenhouse theory can not explicitly explain a hot sunny day at the beach

- Thermodynamics easily explains a hot sunny day at the beach via radiative heating from the Sun along with atmospheric extinction and ground albedo.

Greenhouse theorists treat the entire Earth as a fully-illuminated disk (with no night-time) with -18^{0}C worth of solar heating in their models. This requires one-quarter of the incident solar flux to adjust for the correction factor ratio in going from a spherical surface area (p = 4) to a disk (p = 1).

- Thermodynamics says that this is a physically incorrect model, even as an approximation. It may seem mathematically equivalent to reduce the solar flux by a factor of four, but it is not physically equivalent because the real Earth, which is a sphere, would only come to -59^{0}C on average with 1/4th the solar energy. This is obviously not what is observed!

  Not only is this model physically incorrect even as an approximation, it requires all ground temperatures above -18^{0}C (or is it -59^{0}C?...they don't specify) to be from radiative self-amplification. It does not describe, for example, the surface area of Earth larger than North America continually heated by the Sun every second of every day to potentially anywhere between 40^{0}C and 80^{0}C, or the entire sun-facing hemisphere of the Earth which has a 30^{0}C equilibrium temperature. Clearly, the real source of heating is already explained as being from the Sun, and the average adiabatic atmosphere temperature distribution.

Greenhouse theorists average the solar input heating energy over the entire surface area of the Earth.

- This is the same point as discussed just above, in using a projection factor of p=4. But to make the point more clearly: the entire surface of the Earth is not simultaneously illuminated by the incoming solar energy around all sides, but only half of the Earth is ever actually illuminated. When the solar input heating is incorrectly averaged over the *entire* Earth at once, there isn't a high enough radiative energy flux density to explain why the temperature ever gets above -18^{0}C. Therefore a greenhouse theory must be proposed in order to explain why the ground temperature is +15^{0}C.

  However, if the solar energy is correctly averaged over only the single hemisphere that actually physically receives sunlight, the heating temperature equals +30^{0}C for that hemisphere (and much higher directly under the solar zenith, as we have seen). The +15^{0}C average over both day and night, which is less than +30^{0}C, is then easily understood as simply being due to the fact that the night-side is cooler. Of course, the night-side has to be cooler because it receives no solar energy, but it doesn't cool very fast because of the thermal capacity of the oceans, the ground and the atmosphere. The average temperature of both the day and night hemispheres then comes out to $+15^0$C, which is *less* than the input solar heating, not more.

It is not surprising therefore that in the first case, we need to theorize a greenhouse effect which ends up violating the laws of physics, because the incorrectly calculated temperature is not based on a physically real average in the first place. It is simply wrong to say that the solar energy spreads itself instantaneously over the entire earth at once and reduces the wattage heating intensity by a factor of four. This not the physical situation.

On the other hand, in the latter case, standard thermodynamics, solar heating input, thermal capacity and adiabatic compression, fully explain the temperature and there is no need at all to invent a new radiative self-amplification theory which violates thermodynamics. An unphysical approximation leads to a violation of the laws of thermodynamics, while a physical approximation explains the temperature upon the Earth fully. Only one hemisphere of the Earth is always heated by the Sun, while the other side is always cooling.

The greenhouse theory says that if greenhouse gases increase, the Earth will become hotter

- Thermodynamics says that the only source of heating is from the Sun, with the Laws of Thermodynamics then setting up a temperature distribution going from warm-to-cold off of the ground, with the average temperature obviously found in-between the ground and outer space. The Earth cannot be out of equilibrium with the Sun in the long term because the Sun is the only source of heat for the ground + atmosphere aggregate (assuming negligible geothermal effects). The Earth cannot emit more energy than it absorbs, nor can it less, in the long run. The only way to heat or cool the Earth in the long run is to change the amount of solar energy which is absorbed. This can only be achieved by a long-term change in brightness of the Sun, a change in Earth's albedo or atmospheric extinction, a change in Earth's orbital parameters, etc. Thermodynamics does *not* say it can be done by greenhouse gases, because these gases do not change the input energy. If you do not change the absorbed input energy, you *cannot* change the output energy, and increases in "greenhouse gases" do not change the amount of absorbed input energy.

The greenhouse theory says that greenhouse gases act like a greenhouse around the Earth

- A real greenhouse gets warm because the glass ceiling prevents atmospheric convection. Like sand on a beach, the surfaces inside a greenhouse get warm from the solar energy. The air which is in contact with the surfaces inside the greenhouse then also warms by conduction, and then tries to convect and expand and cool. The glass ceiling prevents this however, and so the warm air stays inside the greenhouse. The greenhouse will therefore warm up to the temperature corresponding to however much total solar energy is being absorbed by the surfaces inside it. And so in fact, a real greenhouse actually prevents the atmosphere from doing what it naturally wants to do, which is cool itself. We build greenhouses because they do the *opposite* of what the atmosphere actually does.

  Therefore, calling back-scattered radiative amplification a "greenhouse effect" is not even an accurate name for the theory in the first place, in any way. Supposed "greenhouse gases" in the free atmosphere do not replicate the behaviour of the solid glass boundaries in a greenhouse, nor do the glass boundaries cause heating by trapping radiation. The atmospheric greenhouse effect is therefore based on a theory which a real greenhouse doesn't do! The abuse of logic in this theory is offensive. If the completely infrared-opaque solid glass barriers of a real greenhouse do not cause the heating inside a greenhouse by reflecting or trapping infrared radiation, then why would merely partial absorption from a trace gas (CO_2 accounts for only 0.04% of the atmosphere by concentration) in the turbulent free atmosphere be able to do what a real greenhouse cannot?

The greenhouse theory says that greenhouse gases trap infrared radiation, and this then warms the surface

- Thermodynamics says that the atmosphere is heated mainly via conduction and convection, and that infrared radiation emitted from the ground could only warm the small fraction of radiatively active gases in the atmosphere, and that no more heat can be created *or* returned to the ground for further warming by that radiation. Additionally, the direction of heat flow is always only from hot (the ground), to cold (upper atmosphere), and then radiatively into outer-space. Infrared energy leaves the atmosphere in only a few milliseconds, even if it gets scattered a couple of times from gases, but this infrared radiation is merely a result of the existing temperature below, not a cause of it, and therefore cannot induce further heating upon its own source. It is informative to consider a vacuum-sealed thermos vs. a thermos sealed with CO_2: the CO_2 sealed thermos will cool *much* faster than the vacuum-sealed thermos – CO_2 does not "trap" any radiative heat.

The greenhouse theory says that the ground surface of the Earth heats the atmosphere through radiative transfer

- Thermodynamics says that the atmosphere is partially heated directly by the Sun via extinction, but is mainly heated from conduction and convection off of the warmer ground. Radiation from the ground can contribute some heat to the atmosphere, but this must be a very tiny amount compared to conduction and convection since the adiabatic temperature distribution already describes the atmospheric temperature, without need for additional temperature forcing from radiation. This is simply because the radiation emitted in the atmosphere is a *result* of its temperature, *not the cause* of its temperature. Additionally, CO_2 only absorbs a small fraction of the infrared energy coming off of the ground, and so partial absorption of radiation near the ground simply cannot provide the same amount (and definitely not more!) of heating that full contact conduction and convection with the ground will already provide. The temperature near the ground surface is determined by the solar input energy upon the ground, and then by conduction and convection of the air upon the ground. The ambient infrared radiation and any radiative scattering after that is a simple result of the temperature of the ground and the air provided by Solar heating, and to argue otherwise violates causality and thermodynamics. Only at high altitude, where the temperature was kinetically actually quite cold, could the merely partial radiative absorption of CO_2 actually constitute a heating effect on the molecule, greater than that which it would have already acquired collisionally. But this would necessarily occur only at cold temperature and high altitude, and so could have no back-effect on the ground far below, which is already much warmer, and the original source of that radiation. Near the ground, where the transfer of heat is dominated by conduction and convection, the oscillatory vibrational harmonic of the CO_2 molecule will already have been excited by physical collisions, and so resonance with that oscillation by the ambient infrared electromagnetic field merely constitutes a scattering effect, which is not a heating effect. In fact, it is likely that high-altitude CO_2 molecules are already oscillating in the vibratory mode in any case, and so even high-altitude resonance between CO_2 and infrared energy would still merely be a scattering effect. If CO_2 increased in concentration, the result would merely be an increase in the scale height of its concentration distribution, with a corresponding increase in the CO_2 scattering altitude of the relevant wavelength; but this would not have any effect on the temperature there, nor far below.

The greenhouse theory says that the thermal radiation of the atmosphere is the *cause* of the temperature of the atmosphere

- The laws of thermodynamics say that the thermal radiation is a *result* of the temperature of the atmosphere. Radiation can only cause heating the first time it is absorbed from the Sun, and after that, no further heating is possible from any re-emission or re-exchange of that energy, as specified by the Laws of Thermodynamics. And so the infrared radiation being emitted and transferred within the atmosphere is simply a result of the temperature, not the cause of the temperature, and to argue otherwise violates causality.

The greenhouse theory says that any additional radiation to the initial radiation absorbed from the Sun can cause further heating, even if it is merely reflected radiative energy emitted from the ground after it was warmed by the Sun in the first place

- Thermodynamics says that only energy with greater energy flux density can induce further heating. It also says that the laws of heat transfer apply to radiation as well as to physical conduction and diffusion. The greenhouse-theory proposal of heat transfer supposes that *any* additional energy put into a system will cause it to warm. However, this is immediately understood to violate the laws of thermodynamics, because even though a bucket full of water at 5^0C contains a great deal of energy, that energy will *not add* to the heat of a bathtub at 40^0C. Only a bucket of water warmer than 40^0C could add heat to the tub. Even if it was a very small bucket with very little total energy as compared to the tub, the small amount of water in the bucket would still be able to heat the tub, a little bit. This is because the water in the bucket has a higher energy flux density, even if it may be a much smaller total amount of energy. Likewise, the thermal radiation emitted by an ice-cube will not cause further heating upon some object which has already been heated by the Sun. Nor would even *all* of the radiation emitted by the ground, reflected back upon itself, cause further heating on the ground than the Sun (the source of the heat) has already provided. We know why a greenhouse gets warm, and that it has nothing to do with the walls of the greenhouse trapping or reflecting (even all of!) the infrared radiation, and therefore by extension we know that the atmosphere couldn't possible do this either. And we also know that the simple proposition of such a scheme violates the Laws of Thermodynamics.

The greenhouse theory says that the temperature on Venus' surface is due to a run-away greenhouse effect from trapping radiation

- Thermodynamics says that because of Venus's very high albedo, there simply isn't enough absorbed radiation in the first place which could possibly explain Venus's very high surface temperature. What could be the source of radiative heating at the surface of Venus if not even that much radiation makes it down to the surface in the first place? Of course, just like on the Earth, the Laws of Thermodynamics require that the radiation at the surface of Venus be the *result* of the temperature found there, not the cause. The *cause* of the temperature found at Venus's surface is the same cause as it is for the Earth's: adiabatic compression and heating, after a radiative thermal equilibrium is established somewhere at altitude, in the atmosphere, with the Sun. But with an atmosphere ninety times more dense than the Earth's, Venus has a much thicker atmospheric depth and therefore a *much* stronger adiabatic compressional heating. In fact, the case of Venus is the strongest evidence one can present in *refutation* of the radiative greenhouse theory, rather than in support of it. If Venus reflects so much incident solar radiation due to its very high albedo, it simply isn't possible for the small amount of radiation actually absorbed to produce the temperature, and the resulting amount of thermal radiation, found at Venus' surface. That would be an obvious violation of the law of conservation of energy and of thermodynamics, and even an introductory course in high-school physics would make clear that this is impossible. So once again we see that the theory of the greenhouse effect is based on an idea which other planetary atmospheres in our solar system don't actually do.

Conclusion

We see that in every single instance of comparison, the Theory of the Greenhouse Effect appears to contradict what the Laws of Thermodynamics have to say about the exact same physical situation. This is very curious because as a scientific theory, it should be in agreement with the pre-established laws of physics. It *may* be possible that the Greenhouse Theory is correct, but, this would require that the Laws of Thermodynamics be not correct. However, if science does not understand the Laws of Thermodynamics, then it must be by pure coincidence that engineers have created such things as refrigerators, internal combustion engines, nuclear power plants, solar panels, and steam engines, just to name a few examples. This doesn't seem likely. Nor would such a conclusion be necessary, when it is the exact same laws of physics which created those examples of our modern technology, which can already readily explain our observations of the temperature of the ground and atmosphere. We do have to conclude therefore, that there is no such thing as an atmospheric radiative greenhouse effect, and the theory which describes it, is a failed theory. What we do have is a Theory of the Thermodynamic Atmosphere Effect, and it is this name, or something like it, which should be used to describe the observed temperatures on the Earth and in the atmosphere, from this point forward.

The conclusion of this article is very simple: there is no such thing as a radiative Theory of the Greenhouse Effect, not in real greenhouses, and certainly not in any planetary atmosphere known to man. The true role of the atmosphere, on Earth, is that it cools the ground, not warms it. Therefore, there is no such thing as Anthropogenic Global Warming or anthropogenic-CO_2 induced climate change, because that supposition is based on the false Theory of the Greenhouse Effect. Any monetary expenditure or political debate on this issue can therefore stop. Now. Or, those can exist only in so far as they are directed to eradicate the false science.

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Ad veritas, ad victorium.

J.E.P.