

THE GREAT GREENHOUSE CONTROVERSY

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SUMMARY: Understanding the Earth's greenhouse effect does not require complicated computer models in order to calculate useful numbers for debating the issue. A solution of the greenhouse problem – if it is a problem – is suggested which does not require industry to reduce its carbon dioxide emission, so avoiding the economic strain this would have, and the socially unwelcome consequences that would follow from it.

INTRODUCTION

Sunlight falling on a plane area facing directly into the Sun, at the Earth's distance from the Sun but out in space, provides an energy flux of $1.36 \times 10^6 \text{ erg cm}^{-2}\text{s}^{-1}$ ($10^7 \text{ erg s}^{-1} \equiv 1 \text{ Watt}$). A rotating sphere without atmosphere instead of a plane area receives on the average per unit area one quarter of this incident flux, $3.4 \times 10^5 \text{ erg cm}^{-2}\text{s}^{-1}$. (The factor $1/4$ arises because the projected area of the sphere is π times the square of the radius, whereas the actual area receiving the sunlight is 4π times the square of the radius). If the sphere were perfectly black the whole of the latter flux would be absorbed and would then be re-radiated as infrared radiation. For a sphere like the Earth with an atmosphere, a fraction of the flux of sunlight is reflected back into space and this fraction does not go into infrared. The problem of determining the fraction reflected back into space, the so-called albedo, is particularly difficult in the case of the Earth, because, of course, the Earth's surface is extremely patchy, as is its atmosphere, which has clouds in some places and not in others. So, one is thrown back at the outset on averages, which is to say on a approximation to the real situation.

Working downwards from the high atmosphere to the Earth's surface, there is molecular scattering (the blue-sky effect), there is dust scattering, there is ozone absorption (which takes place so high in the atmosphere that it hardly affects the greenhouse problem), there is cloud reflection and ultimately, there is reflection from the surface, which can vary from only about 3% from the oceans up to 80% or more from fresh snowfields. The following table gives averages for this hugely complicated situation:

Table 1. Percentage Average Reflectivities from Various Causes.

Source	Percentage Reflectivity
Molecular scattering, dust scattering and ozone	7
Average reflectivity at surface	5
Cloud reflectivity	33

To raise a delicate point, it really isn't very sensible to make approximations like those of Table 1 and then to perform a highly complicated computer calculation, while claiming the arithmetical accuracy of the computer as the standard for the whole investigation. Once the precise detail of the Earth's reflectivity has been lost, the investigation has been so degraded that merit cannot be recovered by attention to arithmetic. Indeed, it seems to me that one cannot then do much better than what now follows.

The absorbed flux of light is re-radiated, mostly at the surface, in the infrared range and approximates a 'black-body' frequency distribution. In this approximation, and calculating without any greenhouse effect for the moment, the re-radiated energy flux is $\frac{1}{4} a c T^4$ erg $\text{cm}^{-2}\text{s}^{-1}$. Here, T is the black-body temperature in degrees absolute, c is the speed of light, and a is the so-called radiation density constant with a known numerical value (7.565×10^{-15} erg cm^{-2} deg $^{-4}$). The factor $\frac{1}{4}$ arises because the infrared is radiated at all angles to the vertical. By equating $\frac{1}{4} a c T^4$, using the known values of a and c , to 1.87×10^5 erg $\text{cm}^{-2}\text{s}^{-1}$ (which balance is required once a steady condition has become stabilised) one easily obtains $T = 239\text{K}$ or -34°C .

This is the base level from which later calculations have to be made. It differs from the temperature the Earth would have in the absence of the Greenhouse in that the value in Table 1 for cloud reflectivity would have to be reduced at such low temperatures. A total reflectivity of perhaps 25 percent, rather than 45 percent would then be appropriate. When the incident sunlight going into heat would be 2.55×10^5 erg $\text{cm}^{-2}\text{s}^{-1}$ rather than 1.87×10^5 erg $\text{cm}^{-2}\text{s}^{-1}$. A similar calculation then leads to 259K or -14°C . This would be the Earth's overall temperature in the absence of the Greenhouse, calculated to a reasonable degree of approximation.

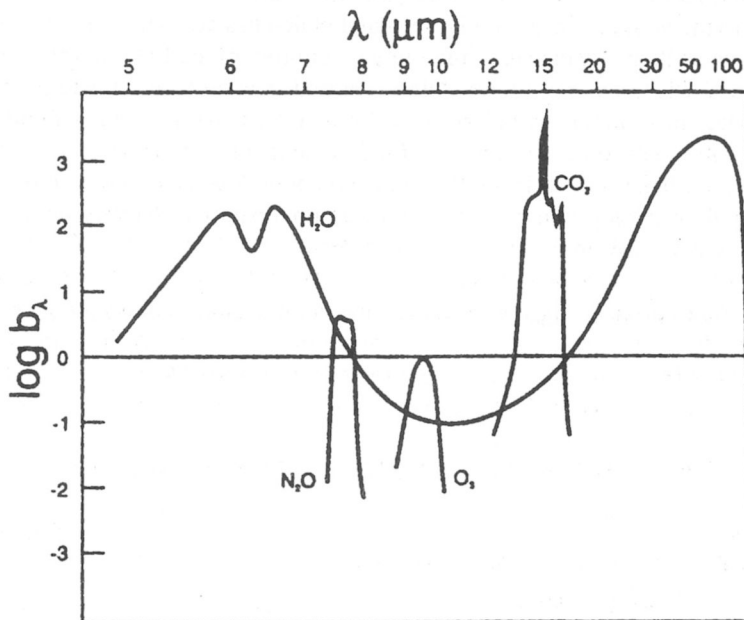


Figure 1.

We have the greenhouse to thank, not to decry, that we do not live in such petrifying conditions. So, turning now to the greenhouse, the necessary data for getting to grips with it was published long ago by C.W. Allen (Athlone Press, Astrophysical Quantities, many editions). Instead of setting out the data in tables, which are hard to digest, Allen displayed it in a diagram whose study is greatly repaying. Figure 1 has been redrawn from his diagram.

Wavelength λ in microns (μm) is given on the abscissa scale. The ordinate scale is the logarithm (base 10) of the quantity which Allen calls b_X , defining b_X as the reciprocal of the number of standard atmospheres that give 50% absorption and 50% transmission (in a standard atmosphere each cubic centimetre contains 2.69×10^{19} molecules). Thus, 1 on the left-hand scale means $\log b_\lambda = 1$, $b_\lambda = 10$, and only one tenth of a standard atmosphere is needed to give 50% absorption. (As well as having a defined molecular density, a standard atmosphere has a defined molecular composition. In Allen's case, the standard molecular composition is such that a whole atmosphere contains 1 gram of precipitable water per cm^2 , and 220 atmo-cm of CO_2 per cm^2 . The latter quantity means that the number of CO_2 molecules contained in the atmosphere per cm^2 of the base area is the same as one gets in 220 cm^3 of pure CO_2 , with each cubic centimetre containing 2.69×10^{19} molecules. That is to say, a total of $220 \times 2.69 \times 10^{19} = 5.92 \times 10^{21}$ molecules of CO_2 per base area of the atmosphere, equivalent to a mass of about 0.12 gram of carbon per cm^2 of base area. Or a total carbon mass of 6.05×10^{17} grams for the whole atmosphere, the atmosphere have a base area of $5.1 \times 10^{18} \text{ cm}^2$.)

These CO_2 values used by Allen in his standard atmosphere are about 20 percent lower compared to the actual present day atmosphere, something which makes little difference to the high CO_2 peak in Figure 1, and which has no significant effect on the following calculations. It increases the global warming effect, but only by a fraction of a degree Celsius. The reason for Allen's particular choice of a 'standard' atmosphere was that the CO_2 concentration coincided with a value for which laboratory data were available. The unit of measurement used in the laboratory data was the atmo-cm (as can be seen below in Table 2). Nowadays, meteorologists seem to prefer giving measurements in parts per million by volume. Conversion is easily made by noting that 1 atmo-cm \equiv 1.25 ppmv.

Table 2. Transmittance Values for Various Wavelengths and Concentrations of CO_2

Wavelength (μm)	CO_2 concentration in atmo-cm					
	500	200	100	50	10	2
18.18	.809	.914	.956	.978	.996	.999
16.7	.063	.165	.282	.421	.707	.888
15.38	.000	.000	.002	.009	.008	.335
14.29	.000	.003	.013	.039	.189	.492
13.33	.199	.341	.466	.594	.824	.941
12.50	.824	.921	.959	.979	.996	.999
11.76	.775	.875	.927	.960	.991	.998
10.53	.949	.978	.989	.994	.999	1.000
10.00	.972	.988	.994	.997	.999	1.000

When $\log b_\lambda = 1$ in Figure 1, a full standard atmosphere would give a very heavy absorption, scarcely emitting at all at the particular values of λ , b_λ , in question. In contrast, $\log b_\lambda = -1$, $b_\lambda = 0.1$ would need ten standard atmospheres piled one on another to give 50% absorption – i.e. giving nearly free transmission. And $\log b_\lambda = 0$, $b_\lambda = 1$ gives 50% transmission for one standard atmosphere.

A line at $\log b_\lambda = 0$ has been added in Figure 1. Wavelengths with $\log b_\lambda$ above this line are mostly heavily absorbed. Wavelengths below it mostly escape nearly freely. This is because the opacity curves for the main greenhouse gases, CO_2 and H_2O , cut the line at considerable angles. This circumstance suggests as an approximation that at all wavelengths for which b_λ is greater than unity (above the line) infrared radiation be taken as so heavily absorbed that nothing at those wavelengths escapes through the greenhouse. And by a like token, at all λ for which b_λ is less than zero (below the line) radiation be taken to escape freely. This way of calculating the greenhouse contains the essence of the matter. Since the treatment of the albedo is already approximate, it makes little sense, in my view, not to take advantage of this immense simplification of the problem. The approximations has the effect of giving free transmission in a band from $8 \mu\text{m}$ to $13 \mu\text{m}$ about, and from a weak spot at $17.5 \mu\text{m}$ to about $22.5 \mu\text{m}$ in the drier regions of the Earth. And also for infrared radiation generated at any appreciable height in the atmosphere. It can be adequately approximated as an escape band from $17.5 \mu\text{m}$ to $20 \mu\text{m}$.

For black-body radiation at the Earth's actual mean temperature of about 290K, the percentages of the total radiation in these two wavebands are 32% and 8% respectively. Thus about 40% of the infrared radiation escapes freely in the above simplified model, and 60% is totally blocked from escape. This forces a return to an infrared temperature T such that 40% of $\frac{1}{4} a c T^4$ equals the energy flux of the absorbed incident light, $1.87 \times 10^5 \text{ erg cm}^{-2}\text{s}^{-1}$. Giving $T = 301\text{K}$, a remarkable increase of 42°C due to the greenhouse.

This is an overshoot when compared to the actual Earth. An overshoot by about 10°C , and the cause of it is not hard to find. It has been assumed that in the blocked wavebands, λ less than $8 \mu\text{m}$, λ between $13 \mu\text{m}$ and $17.5 \mu\text{m}$, and λ greater than $20 \mu\text{m}$, energy is not carried up through the greenhouse by the motion of the air. Since the heat energy of the air molecules exceeds more than ten thousand millionfold, the energy resident as radiation, this is an assumption not likely to be wholly true, And in at least one respect it is certainly incorrect.

Rainfall implies some vaulting of energy up through the greenhouse, weakening its effect to some degree. Latent heat of evaporation of water is carried up, sometimes to considerable heights, and is released again when droplets condense. Travellers by air, particularly in the tropics, will be familiar with the immense clouds that boil up to the tropopause, or heights above 35,000 feet. The latent heat of condensation of water droplets in those clouds has vaulted much of the greenhouse. The amounts of energy so involved are by no means small. Thus the energy needed to evaporate 1 inch of rain is equivalent to about three days of sunshine. In regions of high rainfall there may be as much as 100 inches of rain annually, so in those region as a considerable fraction of the energy of the incident optical light goes into evaporation of water, and thence evades at least some of the greenhouse. The outcome being for the free band from 17.5

um to 20 μm to be widened at its upper bound – the lower bound of 17.5 μm is less affected since the core of the carbon dioxide absorption extends well above the tropopause. The nett effect is to lower the calculated 301K towards 290K.

I come next to the effect of varying the CO_2 concentration. The calculation now requires the data set out in Table 2. The second column of the table is adequately close to where we are today, while the first column is where the atmosphere will be if fossil-fuel consumption continues at the present rate to 2050. The numbers in the second column show that the free band from 8 μm to 13 μm , used in the above calculation, would be more accurate if taken from 8 μm to 13.1 μm . and for the first column taken from 8 μm to 12.93 μm , thereby narrowing the band is slightly in the ratio $(12.93-8)/(13.1-8) = 0.9667$. Previously, we had a 32% transmission through this band. But with the enhanced CO_2 concentration of 500 atmo-cm, the transmission would then be close to $32 \times 0.9667 = 30.93\%$, slightly less than before. And similarly, the other free band from 17.5 um to 20 um would be narrowed so as to carry 7.69% instead of 8%. These percentages being of the energy in the whole infrared spectrum. For a total transmission of 38.3% instead of 40% Thereby increasing the calculated temperature by the difference between $239/(0.383)^{1/4}$, which is 3K. It is well-known that difference calculations of this kind are usually more accurate than either calculation is separately. This is because the errors are essentially the same and therefore cancel when the difference is taken. It is also well-known that manifest calculations like this are likely to be broadly trustworthy in their results, whereas sometimes one can be deceived by inaccessible, extensive computer calculations, especially if the computer belongs to someone else.

The results of 3K actually agrees quite well with computer calculations, indeed with what are supposed to be the best of them. The advantage of overtness is that we see immediately that the 3K result is contingent on nothing but the CO_2 concentration being changed. Which is certainly not correct. A raising of the Earth's mean temperature from 290K to 293K would inevitably produce more evaporation of water vapour from the oceans. The saturation vapour pressure of water rises by as much as 20% between these temperatures. Inevitably then, there would be more cloud and more reflection of sunlight by clouds, lowering the flux of sunlight getting through to the Earth's surface and consequently increasing the Earth's albedo. Taking account of this effect, it is not hard to see that an increase of cloud reflectivity by 2%, from 33% in Table 1 to 35%, would cancel a half of the enhanced greenhouse, cutting the above rise of 3K to 1.5K. (And of course, cutting the rise in the saturation pressure of water vapour from the above 20% to 10%.) To argue that a 10% rise in the water content of the atmosphere would not generate a 2% rise in cloud reflectivity seems to me hazardous. And yet this is what the computer enthusiasts seem to have done. The lesson, in my own experience, is that while one can safely leave arithmetic to a computer, one should never leave physics to it.

So, it is necessary to split the calculated greenhouse enhancement of 3°C into a part that is a genuine rise and a part that is self-cancelling. The way I like to proceed in a situation like this is to follow the judgement of Solomon: to split things down the middle, 1.5°C self-cancelling, 1.5°C a genuine rise. Leaving me to continue with a little sociology, which frankly, is not my subject, but it is one that we all get tempted into

from time to time. Given the choice, I imagine nobody would opt for a world without any greenhouse, that is, a world with a mean temperature of about 259K. And probably few would opt for an ice-age world with a mean temperature of 275K to 280K. To this point the greenhouse is seen as good. Further still, a majority clearly continues to see the greenhouse as good up to the present-day mean of about 290K. But, at the next 1.5K a drastic change of opinion sets in: the greenhouse suddenly becomes the sworn enemy of environmental groups, world-wide, to the extent where they rush off to Rio and elsewhere and make a great deal of noise about it. I find it difficult to understand why. If I am told that computer calculations show immensely deleterious consequences would ensue, then I have a good laugh about it. In private, of course, since I am always careful to be polite in public.

I have also found it good policy, whatever one might feel about something in private, to take up a humble attitude about it in public. So I will assume from here on that those who feel that, while a 35°C greenhouse effect is cornucopian, a rise by 37°C would be tantamount to Armageddon, are correct in their views. The inference then is that something must be done to stop the CO₂ concentration from rising in the atmosphere from its present-day value of about 250 atmo-cm to its projected value to 500 atmo-cm in the year 2050. My purpose being to show that such an objective can be achieved without ruining the world's industries and so bringing on a situation which potentially could have the eventual effect of returning us all to the Dark Ages.

If CO₂ is to continue to be emitted into the atmosphere and yet not to accumulate there, it must be stored in some way as it is produced. A physically possible storage place would be the cold waters of the deep ocean, but this does not seem seriously practicable, at any rate at the present time. Storage in trees has also been considered, but this does not work out too well either, when the details are considered.

Densely-packed, spindly forest trees have a rather low mass of about 10⁵ grams, a tenth of a ton. They each occupy two or three square metres of ground area for a mass surface density of a few grams per cm², about 1 g cm⁻² of which is atomic carbon. The amount of atomic carbon in the present atmosphere was noted above to be 6.10¹⁷g, and a similar quantity is required to be stored up to the year 2050. This would require a forested area of spindly trees amounting to about 6.10¹⁷ cm², which is not far below the whole land area of the Earth north of latitude 55°.

Going from spindly trees to stately parkland trees does not help. Stately trees have masses that are an order of magnitude or more greater than spindly trees, but what they gain in individual mass, they lose in the ground area required for their roots and for access to sunlight. The conclusion is, therefore, that trees will not do: the required area of forest is too large.

Deep bogs, swamps and marshes contain at least one hundred times more carbon per unit area than dense forests, with peat deposits running to depths of up to 10 metres, such as can be found in the great bog of central Ireland.

The carbon stored in deep bogs, swamps and marshes, is of the order of 199 gram cm⁻². At this area density about 1% of the land area north of latitude 55° would need to be set aside as wetlands in order to take up the industrial emission of CO₂, with plenty of time before the year 2050 to get it done. The essential point being to ensure that the chosen areas are sufficiently badly drained to prevent oxidation of carbon back

into the atmosphere, and to take such steps as would encourage the growth of vegetation in those areas.

My last question is whether such a degree of carbon storage has ever actually happened. The present-day existence of the remains of deep bogs suggests that it might have done. With the effect of taking down the atmospheric concentration of CO₂ to the region of 50 atmo-cm. Something of the sort was suggested long ago by Svante Arrhenius as the cause of the ice-ages.

Were all CO₂ removed from the atmosphere, the escape band for infrared would go the whole way from 8 μm to 20 μm, which would cover a fraction 0.6 of the infrared. The greenhouse would then produce a temperature rise, assuming the H₂O greenhouse was not concurrently affected, from 239K to $239/0.6^{1/4} = 271.6\text{K}$.

This would overshoot the lowering of temperature required for an ice-age. However, bogs could never grow to the extent of entirely taking out all CO₂ from the atmosphere. Some CO₂, about 50 atmo-cm, would remain essential for biological activity to continue, giving a greenhouse producing a temperature intermediate between 271.6K and 290K. Explaining perhaps, why typical mean temperatures in the ice-ages were around 280K.

It is known that the last ice-age ended with great rapidity in the Allerød/Bølling about 13,000 years ago. Thus a viable theory of the cause of ice-ages must explain why, after ice-age conditions had persisted for most of the preceding 100,000 years, the ice-age was suddenly gone in less than a millennium. Possible even in a few centuries. The answer, I suspect, was the CO₂ stored in deep bogs was rapidly returned to the atmosphere by oxidation, by fires. Peat bogs are unstable against fire. This is because the energy from the combustion of an appreciable volume of bog is considerably greater than the energy needed to dry out a similar volume, which then continues the burning.

So, what could cause such fires? It is attractive, it seems to me, to suggest the arrival of a giant comet in a suitable orbit, as proposed by Clube and Napier. With the fires started by tunguska-like bolides impacting areas of high carbon storage.

This view has the advantage that it explains why, in the remote past, ice-ages have generally persisted for long periods of the order of 100,000 years. Then they have disappeared suddenly, only to reappear after a few thousand years of warmer interglacial conditions. Because suitable giant comets are generally interspersed by intervals of the order of 100,000 years. In past times, it was necessary to wait 100,000 years before such a comet arrived. But then, once the comet was broken up and its pieces gone, the bogs slowly returned, abstracting the CO₂ from the atmosphere once again, in an irregular progression as drainage conditions influencing bog formation fluctuated.

This seems to make sense in a way that I have never found other theories to ice-age do. It implies that, so long as man remains able to control drainage patterns, there will be no further ice-age.

It should be noted, however, that the deep cold waters of the ocean contain enough dissolved CO₂ to supply the present atmospheric amount more than thirty times over. Moreover, there is an interchange of deep water with surface water, usually supposed to be too slow to affect the global warming controversy, but relevant on the time-scale of an ice-age. Unless the ice-ages were also associated with an interruption of this cir-

ulation. Or unless CO₂, once dissolved in the deep ocean, diffuses so as to remain there whatever the water may do. Because CO₂ is significantly more soluble in cold water than it is in warm could be the reason why the CO₂, once it gets deep, stays deep, not being stirred up again.

REFERENCES

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