Is a Greenhouse Heated by Radiation Trapping or Convection Blocking?

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Abstract

In the climate science literature, there are many references to an experiment performed by Prof. R. W. Wood in 1909 which led him to conclude that the main cause of heating in a greenhouse is by blocking air convection. Based on Wood's article, global warming skeptics have argued that the "greenhouse effect" due to trapping of radiation by the atmosphere is false. It seems strange that a brief note published over a century ago should continue to be invoked to cast doubt on climate science today. This article reviews recent efforts to replicate Wood's experiment (including new ones I conducted) and concludes that Wood was mistaken. The "greenhouse effect" – at least as applied to a real greenhouse – is heated primarily by selective filtering of infrared radiation.

Introduction

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) is the United Nations body for assessing the science related to climate change. Since 1990 the IPCC has assembled large working groups of scientists across the world to provide the most reliable account of the Earth's climate and its changes. Throughout the IPCC reports, the blame for recent global warming and climate change is traced to increased "greenhouse gases" in the atmosphere. The work of Fourier in the 1820s is cited as the origin of the "greenhouse effect" analogy which explains heating in a real greenhouse. In Fourier's account, solar radiation enters through the transparent glass, but because glass is opaque to infrared light, radiation emitted from the warm ground gets trapped [1].

It is important to clarify whether the greenhouse analogy is valid or not. The reason is that numerous climate skeptics have sought to refute the main claims of the IPCC based on an alleged failure of the analogy. Skeptics frequently cite a brief note from 1909 by Professor Robert W. Wood of Johns Hopkins University [2] to make their case. Wood doubted Fourier's theory based on radiation trapping. He performed an experiment comparing boxes with a pane of glass and a pane of crystallized rock salt (sodium chloride) which is transparent to infrared radiation. Since he found no difference in temperature, he concluded that greenhouses work merely by preventing convection, a mechanism that is not applicable to the open atmosphere. Based on Prof. Wood's conclusion, skeptics argue that the atmosphere doesn't warm the earth due to radiation trapping, and the "greenhouse effect" analogy to the atmosphere is erroneous.

Here are some dramatic headlines of recent articles making this point:
"Greenhouse Gas Theory Trashed in Groundbreaking Lab Experiment" [3]
"New Paper Discrediting Basis of Theory of Man-Made Global Warming"[4]
"The Shattered Greenhouse: How Simple Physics Demolishes the 'Greenhouse Effect"' [5]
"The Fraud of the Atmospheric Greenhouse Effect" [6]
"R.W. Wood Had it Right: Sun Heats Earth!" [7]

Even among some mainstream scientists, acceptance of Wood's conclusion is apparently widespread. Here are some examples:

National Oceanography and Atmospheric Administration (NOAA):

> Note: This atmospheric process is referred to as the Greenhouse Effect, since both the atmosphere and a greenhouse act in a manner which retains energy as heat. However, this is an imperfect analogy. A greenhouse works primarily by preventing warm air (warmed by incoming solar radiation) close to the ground from rising due to convection, whereas the atmospheric Greenhouse Effect works by preventing infrared radiation loss to space. Despite this subtle difference, we refer to this atmospheric process as the Greenhouse Effect and these gases as Greenhouse Gases because of their role in warming the Earth.[8]

American Chemical Society:

> The atmospheric gases and a greenhouse work in quite different ways, but the resulting effect, higher temperature in both cases, has led to the nomenclature "greenhouse gases" for the

> atmospheric gases responsible for the atmospheric warming effect. Although this nomenclature is misleading, it is in such common use that we use it here as well. [9]

American Institute of Physics:

> The key publication explaining that greenhouses are kept warm less by the radiation properties of glass than because the heated air cannot rise and blow away; see Wood (1909); for the science... [10]

Even Carl Sagan disputed the greenhouse analogy in his famous global warming testimony before Congress in 1985, in which he defended the greenhouse effect in the atmosphere but added that "It is a misnomer because that is not how a florist's greenhouse works, but that's a very minor point." [11][1]

There are also abundant YouTube videos on the greenhouse effect, of varying quality.

It seemed strange to me that a brief article published over a century ago should continue to cast doubt or confusion considering today's massive efforts in climate science. I decided to review the literature on Wood's experiment and related experiments, then to conduct my own.

Professor Wood's Experiment

Prof. Wood's greenhouse experiment appears simple enough. Here is the section of Wood's article that describes his experiment and its result:

> To test the matter I constructed two enclosures of dead black cardboard, one covered with a glass plate, the other with a plate of rock-salt of equal thickness. The bulb of a thermometer was inserted in each enclosure and the whole packed in cotton, with the exception of the transparent plates which were exposed. When exposed to sunlight the temperature rose gradually to

[1] At 4:40 Sagan stated correctly that the atmosphere is opaque at 15 microns. So is glass, by the way.

> 65 C., the enclosure covered with the salt plate keeping a little ahead of the other, owing to the fact that it transmitted the longer waves from the sun, which were stopped by the glass. In order to eliminate this action the sunlight was first passed through a glass plate.
>
> There was now scarcely a difference of one degree between the temperatures of the two enclosures. The maximum temperature reached was about 55 deg. C. From what we know about the distribution of energy in the spectrum of the radiation emitted by a body at 55 deg. C., it is clear that the rock-salt plate is capable of transmitting practically all of it, while the glass plate stops it entirely. *This shows us that the loss of temperature of the ground by radiation is very small in comparison to the loss by convection*, in other words that we gain very little from the circumstance that the radiation is trapped.
>
> Is it therefore necessary to pay attention to trapped radiation in deducing the temperature of a planet as affected by its atmosphere? The solar rays penetrate the atmosphere, warm the ground which in turn warms the atmosphere by contact and by convection currents. The heat received is thus stored up in the atmosphere, remaining there on account of the very low radiating power of a gas. It seems to me very doubtful if the atmosphere is warmed to any great extent by absorbing the radiation from the ground, even under the most favourable conditions. [Italics mine.]

Notice that Wood's article concerns two distinct questions:

1. What is the mechanism of heating in a greenhouse – blocking convection or trapping radiation?

2. What is the mechanism of global warming in the atmosphere?

Wood's experiment only directly addresses question 1. The analogy to the atmosphere is only valid if heating in both cases is due primarily to radiation trapping. Simple experiments only can address the first question, and Wood's answer is that radiation trapping is **not** the main mechanism of heating a greenhouse. The physics of atmospheric heating is clearly much more complex and will not be addressed here; an excellent brief review of the theory is provided by Pierrehumbert (although he too denied the analogy to a greenhouse). [12]

Experimental Tests of Wood's Conclusion

Interestingly, a critique of Wood's conclusion was published already *in the same year, in the same journal*, by C.G. Abbot, Director of the Smithsonian's Astrophysical Observatory. [13] He questioned the conclusion that heat loss was mainly due to convection. To reduce convective heat loss, he made a triple-glazed cover for a box on the ground. On a clear November day in 1909, Abbot measured the internal temperature. He also used Planck's blackbody radiation formula to calculate the heat balance of this setup and concluded that "...there is reason to think that 'trapping' is more important perhaps than Professor Wood thinks."

Dr. Abbot did not use a control, but his use of triple glazing was an elegant way to reduce convection and test Wood's conclusion. Another difference from Wood's experiment was the presence of the ground. Wood's insulated boxes had no mass load to absorb heat. This meant that the temperature in his boxes was dependent on the precise position of the thermometers and could vary due to stratification of heated air. If one intends to simulate the mechanism of warming of the Earth with a tabletop experiment, it is necessary to include something that simulates the ground!

It would seem that a retraction or at least further study was in order. But I could find no further discussion of this question between Wood and Abbot in the literature.

More recently other experimenters have attempted to replicate Wood's experiment, with modifications. For one thing, it is very problematic to use salt as a window – it is fragile and difficult or costly to obtain in clear form. Nowadays it is unnecessary to use a window made of salt to provide transparency in the infrared; polyethylene (PE) is a much more convenient substitute. It is essentially transparent in the infrared to beyond 20 microns, except for a few narrow bands. Polyvinylidene chloride film (PVC, food wrap) is another useful option. Figure 1 shows the infrared spectral transmittance of these films.

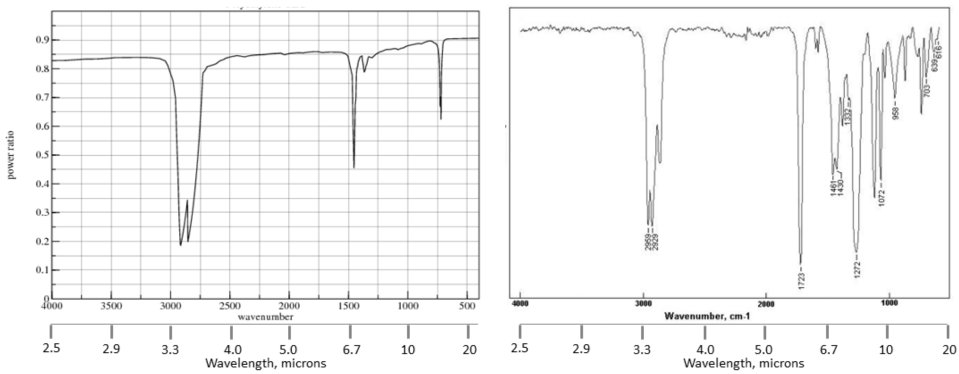

Figure 1: Infrared transmittance of polyethylene
and polyvinylidene chloride films (ref. [14] and [15])

Pratt's experiments

In 2009 Vaughan R. Pratt, a Stanford University professor, posted his work on a web page. [16]

It was titled, "Wood's 1909 greenhouse experiment, performed more carefully." He noted that Wood's article was "seriously lacking in detail." Wood provided no dimensions, and no diagrams or graphs of temperatures.

Pratt observed strong thermal stratification of the air in the box, which is not surprising. This implies that it would be difficult to make meaningful air temperature measurements in any experiment: the readings of the sensors are very sensitive to their position: "The variation within the boxes dwarfs the variation between the boxes," thus making his experiment inconclusive regarding the first question. Pratt could not resolve the question with this apparatus, because it attempted to replicate Wood's misguided experimental setup that did not include a thermal load.

Nahle's experiments

Nasif S. Nahle in Mexico attempted to "replicate" Wood's experiment and "verify" his conclusion.[17] His rather elaborate report has tables showing similar temperatures (within one degree) attained in the boxes for all window conditions. I think what could explain this similarity is that air circulated inside the boxes and quickly heated up to the same equilibrium temperature in all cases. As in Wood's experiment, there was no thermal mass in the boxes, just air. So, all the boxes heated up very fast to about the same equilibrium temperature.

From Pratt's and Nahle's experiences we learn that it is not prudent to attempt to replicate Wood's experiment. It is only necessary to perform any experiment that resolves the specific question about the mechanism of heating in a greenhouse. All the attempted replications do is to show that Wood's setup is not able to answer this question decisively. The experimental design must be modified by including a thermal mass and replacing the salt window. Or an entirely different experiment, such as the one used by Abbot, may provide a clearer answer.

Spencer's experiments

Meteorologist Roy Spencer has spent years discussing all aspects of the climate change questions in detail on his blog. On the question of the greenhouse effect, he even went to the trouble to study the question experimentally. He first quoted Wood's article in its entirety. Then he reviewed the experimental work of Pratt and Nahle. Spencer was not misled by Wood's faulty experimental design: "I'm more interested in doing the experiment the right way than in trying to replicate an experiment where so many details are missing, and we have better methods available anyway." [18]

Spencer realized that Wood's use of a salt window is unnecessary. Spencer used a comparison of insulated boxes covered with either clear food wrap or an acrylic ("plexiglass") sheet for his experiments. Acrylic is an absorber of IR, like glass. The composition of food wrap varies. Some is made of polyvinylidene chloride, which has some absorption bands in the IR, but is probably adequately transparent for this experiment. Spencer reported that "we clearly see the warming effect of the plexiglass. Even though the plexiglass only passes 92% of the visible sunlight, which by itself should cause cooler temperatures, its presence over one box causes that box to warm relative to the other box (or, you can say its absence causes the other box to run cooler). This is how the 'greenhouse effect' works."

Spencer's experiment did not contain a thermal load in the boxes, and his time-series plots in varying sunlight are confusing. However, his conclusion is unequivocal: "convective inhibition cannot explain the warming effect of the plexiglass. It must be an infrared effect." [19]

New Experiments

For the past several years, I have been conducting experiments to measure the performance of solar thermal cookers, which are household-scale devices for cooking food with concentrated solar radiation. In 2015 I participated in meetings of the Clean Cooking Alliance [20] to develop standards for power, efficiency, emissions, safety, and durability of cookstoves, including solar cookers [21, 22, 23, 24]. This work involved development of instrumentation and protocols for testing these devices, so it was straightforward to adapt these to address the question of the greenhouse effect.

My new experiments were not intended to replicate Wood's experiment, which was ill-conceived in some ways as discussed above. Rather, it was simply an attempt to understand the physics well enough to answer question no. 1: the mechanism of heating in a real greenhouse.

As in Spencer's experiments, I used two Styrofoam boxes for the comparison of two window materials: ordinary glass in one and thin polyethylene film in the other. I mounted the boxes on a tilt table so that they could be easily aimed in the Sun's direction and turned to maintain a nearly constant solar irradiation. To provide a thermal load (which was missing in previous experiments), in each box I included a thick copper plate (because copper has low heat capacity and high thermal conductivity). To speed up the heating further, I painted the interior of the boxes with Krylon #1602 Ultra Flat Black spray paint (emissivity greater than 0.96 from 2-5 microns [25]). I painted the plates with a special artist's black paint, which appears blacker than the Krylon paint at least in the visible spectrum [26].

I did adopt one feature of Wood's experiment that was sensible: I mounted glass plates above both boxes, in order that the incoming radiation into the boxes was pre-filtered to include only visible light and not the IR radiation from the Sun. In this way, both black plates received nearly the same incoming radiation. This prevented a misleading conclusion due to IR from the Sun that might heat the box with polyethylene more than the box with the glass window. Also, the pre-filter glass sheets were mounted on standoffs above the boxes to allow free convection, and the sheets were tilted at a 45° angle so that any back-reflections from the boxes were deflected to the sky.

The sensors for the experiments consisted of pairs of thermocouples that were bolted to the centers of each of the black plates. These were connected to a datalogger via cables that reached into the boxes through a 2 cm hole in the lower side of each box. In other words, there was no attempt to seal the boxes against pressure (as one experimenter prescribed [27]). In effect, the solar radiation was intended to heat the interior of the boxes as in heating a room in a house. In such a situation, isostatic pressure applies. (Strangely, the thermodynamics of this ordinary process has only recently been derived from first principles [28].)

In addition to the plate thermocouples, an external instrument package (a "Stevenson box") was built to measure local solar irradiation, ambient temperature, and wind speed. Three pyranometers were included; two measured global horizontal irradiance (GHI) and one was mounted on the tilt table to measure global tilted irradiance (GTI). The pyranometers provided a quantitative measure of the solar power coming into the test boxes. [29]

Figures 2 and 3 show the typical experimental setup used for the experiments. Tables 1, 2 and 3 provide details on the dimensions of the test boxes and cover materials.

Figure 2: Experimental setup for comparison experiments. The white box is a "Stevenson box" containing weather instruments, powered by the solar panel on the ground. Each test box has a black frame holding a sheet of window glass at a 45° angle. Cables from 2 cm holes in the bottom of each box are connected to thermocouples to measure internal black plate temperatures. A data logger is connected to the cables behind the tilt table.

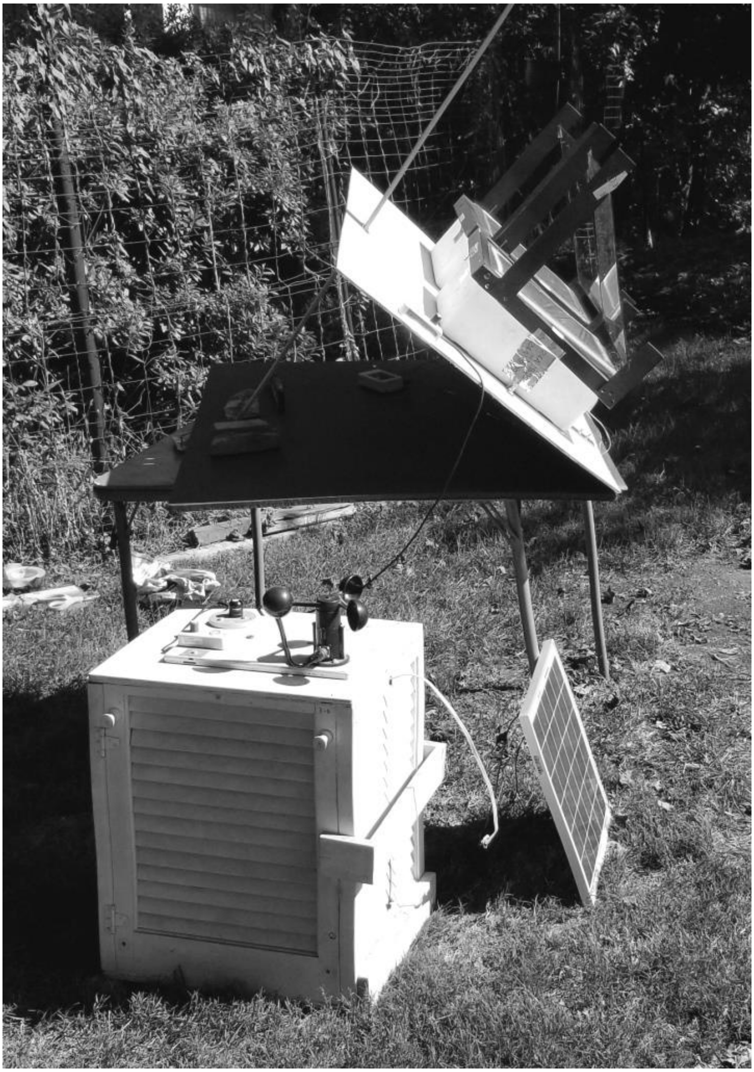

Figure 3: Side view of experimental setup showing two test boxes mounted on a tilt table to allow the boxes to be pointed in the Sun direction. Glass prefilter sheets can be seen mounted in frames in front of the boxes. There is a 4 cm air gap below the sheets to permit free convection over the boxes. A pyranometer is mounted on the tilt table for measuring global tilted irradiance (GTI), and two more are mounted on top of the Stevenson box to measure global horizontal irradiance (GHI), along with an anemometer. The Stevenson box also contains a solar panel charge converter and a data logger for storing measurements.

Table 1. Test apparatus materials

Item	Material
Insulated boxes	Styrofoam
Mass load in each box	Copper
Glass box cover	Soda-lime glass
IR-transparent cover	Polyethylene film
IR-transparent cover	Polyvinylidene chloride
Tilt table	Plywood
Prefilter sheets (2)	Soda glass
Frames for prefilters (2)	Wood

Table 2. Test apparatus dimensions

Item	Dimensions, in	Dimensions, cm
Insulated boxes	11.75 x 11.75 x 5.75	29.8 x 29.8 x 14.6
Mass load in each box	8 x 8 x 1/4	20.32 x 20.32 x .3175
Glass box cover	9.5 x 9.5 x 3/32	24.1 x 24.1 x .238
IR-transparent cover	0.00025	0.00063
IR-transparent cover	0.0003	0.0007
Tilt table	24 x 48 x 1/4	132 x 61 x .635
Prefilter sheets (2)	13 x 14.5 x 3/32	33 x 36.8 x .238
Frames for prefilters (2)	12 x 12 x 9.5	30.5 x 30.5 x 24.1

Table 3. Heat capacities of materials

Item	Mass	Heat capacity, J/kg K
Copper plates, each	1.179 kg	385
Glass cover (heated portion only)	0.292 kg	840
Styrofoam box	0.185 kg	1215 approx.

Experimental Data

Calibrations

Preliminary tests were done to ensure that thermocouple readings had small systematic errors. When cooled to ambient temperature

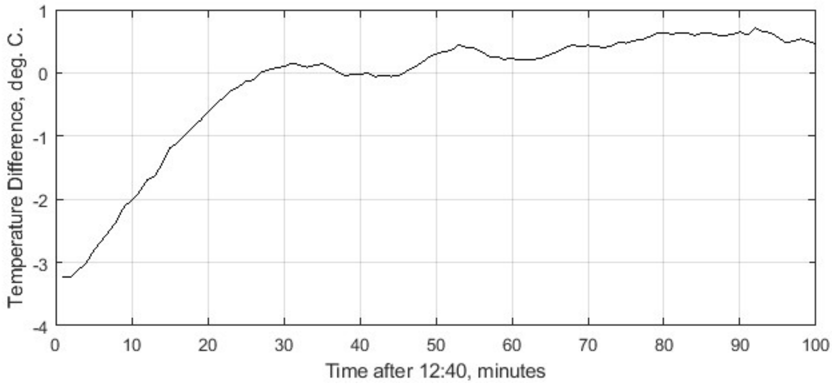

Figure 4: Differences between plate temperatures
in two boxes with PE covers (Experiment 15).

overnight, temperature readings of all four thermocouples converged to within a range of 0.2° C.

Controls

It was necessary to determine any temperature differences between the two boxes when they both had the same cover material. Control experiments were performed in which both boxes had polyethylene covers. These experiments showed minor temperature differences of less than 1° C once the boxes heated to equilibrium. Figure 4 shows a typical example of the temperature differences between the black plates in a control experiment.

Comparisons

Once it was clear that the temperature measurements had adequately low systematic and random errors, comparison experiments could commence. These experiments were only done when the sky was clear and average wind speed was less than 1 m/s. Figure 5 shows a typical example of the heating curve for a comparison experiment. The upper curve shows the temperatures of the plate in the glass covered box; the lower curve is for the plate in the polyethylene covered box. Temperatures in both boxes

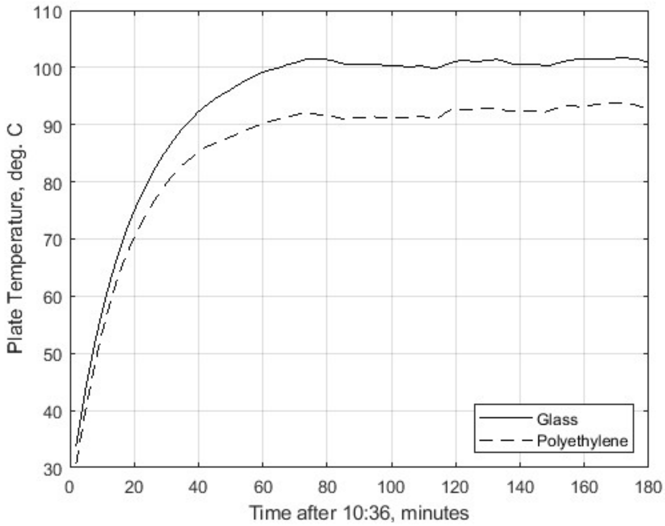

Figure 5: Plate temperatures in two test boxes for Experiment 18

rose to equilibrium in about 80 minutes. The typical difference in temperatures was 8 degrees C. Measurements were made over a range of ambient temperatures from 5° to 25° C, but the mean temperature differences were consistently 8 to 10 degrees C. The glass-covered box always had higher plate temperatures.

Summary of Experimental Results

A series of experiments was conducted in the fall and winter of 2022-23. It was of interest to select clear days with high and low ambient temperatures. Table 4 shows a summary of the results of both the control and comparison experiments (nos. 1-13 were for setup and calibrations). Note that two of the comparisons were done without the prefilters in place; these experiments showed higher temperature differences, as would be expected. The main conclusion is that (with prefiltering) the glass-covered box was an average of 8 degrees C higher than the polyethylene (PE) film-covered box. This is significantly higher than the standard deviation of the differences in the controls, which was less than 1 degree C.

Table 4. Temperature Difference Data
Glass or PVC box minus PE box at Equilibrium, degrees C

No.	Date	Conditions	Ambient	*	Difference
14	20221006	Control (2 PE boxes)	26	On	2
15	20221007	Control (2 PE boxes)	28	On	0.5
16	20221009	Comparison, glass vs. PE	20	On	10
17	20221010	Control (2 PE boxes)	22	On	±2
16	20221009	Comparison, glass vs. PE	20	On	10
18	20221011	Comparison, glass vs. PE	25	On	8
19	20221021	Comparison, glass vs. PE	23	Off	13
20	20230211	Comparison, glass vs. PE	11	Off	12
21	20230214	Comparison, glass vs. PE	16	On	8.5
22	20230218	Comparison, glass vs. PE	5	On	8
23	20230223	Comparison PVC vs. PE	23	On	1

* Prefilters On/Off

As is evident from the control experiments, the boxes are very similar and capable of resolving differences of 1 degree C or less. It was consistently observed that the plate in the glass-covered box reaches higher temperatures than the polyethylene-covered box by 8 degrees C or more. This result was not significantly affected by ambient temperatures in the range from 5° to 25° C.

These empirical results could still be questioned, based on the obvious fact that they were not obtained from measurements of a real greenhouse. However, what is of interest here is not a greenhouse per se but the mechanism of heating in the "greenhouse effect," and this can be adequately studied using small boxes. Further understanding of the heating mechanisms can be sought via a mathematical model based on established thermodynamics theory.

Simplified Thermodynamic Model of the Test Boxes

It will be instructive to consider a simple thermodynamic model of the experiment. The purpose of this section is not to derive a complete or rigorous model, but only enough to allow us to understand the relationships of the variables involved in heating and cooling, and to quantify the parameters that affect the heating of the test boxes.

Consider an insulated box with a window and an internal metal plate that is heated by the Sun. The energy input to the box includes solar radiation across the visible spectrum. Of course, the solar irradiance varies with time t due to solar elevation, clouds etc. so we will just call it $G(t)$. For any object in the outside air, heat loss occurs by convection and radiation (loss due to conduction is included in the loss due to convection). Newton found that heat loss due to convection is proportional to the difference between an object's surface temperature T and the ambient temperature T_a (Newton's law of heating and cooling). In the late 19^{th} century, Stefan and Boltzmann found that radiation loss has a fourth power dependence on the temperature difference between the object's temperature and the temperature of the surrounding radiation from the sky T_s. Combining these two laws for heat change dQ in Watts leads to a differential equation [30]:

$$dQ = mC_{\nu}\frac{DT}{dt} = G(t) - hA(T_a - T) - (A\epsilon\sigma T^4 - Aa\sigma T_s^4) \qquad (1)$$

Here, m is the mass of the object, C_{ν} is the heat capacity of the object, A is the area of the object exposed to the Sun and h is the heat transfer coefficient for the object. The last term is the Sefan-Boltzmann equation for radiation loss, in which dimensionless parameters ϵ and a are the emissivities of the object and the sky respectively, and σ is the Stefan-Boltzmann constant, which is 5.67×10^{-8}W/m K.

If the "heated object" is really a system with various parts, a boundary can be placed around it, and this equation can still be used, provided the masses, heat capacities and other parameters can be combined and treated as one object with a characteristic size L, under the restriction that

$$Bi = hL/k < .002 \qquad (2)$$

where Bi is the Biot number, and k is the thermal conductivity of the object. In the case of an object with internal fluid circulation such as a greenhouse or a heated box, the conductivity can be assumed to be high, so under this restriction we can model the heating or cooling of the object with equation (1). This equation then represents the (simplified) transient lumped-parameter model of the test box. Since the dominant thermal load of the test box is in the black plate, the solution of this equation describes the overall change in temperature T(t) of that plate over time.

Equation (1) describes the functional relationships of the important variables by placing experiments into the context of well-established physical theory. This reduces into mathematical form the first question that Wood addressed: which term – convection or radiation – contributes more to the heating of an object like a greenhouse? We answered this question experimentally, but it is also helpful to examine it mathematically to quantify and generalize the conclusion.

Convection loss from the glass window

As the test box is exposed to sunlight it is heated, and free convection draws energy away at a rate determined by the convection loss coefficient h. In estimating convective heat loss in the test boxes, what matters is the surface that is exposed to the ambient air, not the internal copper plate temperature. A rigorous calculation of the temperature of the glass would need to include the heat transfer from the internal plate through the glass to the ambient air – in other words, it would require a more complex calculation than the simplified lumped-parameter model. In mathematical terms, this is a conjugate problem [31].

Rather than pursue this calculation, I simply used a hand-held pyrometer to measure the temperature of the glass window. Pyrometer measurements at equilibrium showed temperatures of 42-47° C across the glass when the ambient temperature was 15° C. To first order, this is roughly halfway between the temperatures of the copper plate and the ambient.

A formula for h for free convection over a heated vertical plate can be found in textbooks [32]. Such formulas are empirically derived correlations given in terms of the dimensionless Nusselt number Nu, or equivalently the Grashof number Gr and the Prandtl number Pr. These numbers are based on properties of air and the plate dimensions. Substituting these values into the correlation formula for a 46° C vertical surface gives $h = 4.9$ W/m^2. This is similar to the plotted value of $h = 4$ at very low wind speed (0.1 m/s) in ISO standards [33, 34]. However, with the tilted ($\sim 50°$ from vertical) glass window in our experiments, these correlation formulas are likely to give only a rough approximation since the flow probably separates rather than forming a laminar boundary layer as assumed in correlation formulas. Also, slight wind drafts may increase the heat loss.

Effect of wind speed on *h*

Clearly there will be some wind speed at which convection loss will exceed radiation loss. A worst-case calculation for the value of h assumes that the wind is moving in the same direction as the free convection, i.e., this becomes a forced convection calculation. Formulas for the forced convection coefficient over a vertical flat plate are given in terms of a combination of the Reynolds number and the Prandtl number [35]. The Reynolds number is defined as $Re = uL/n$, where u is the flow velocity and n is the kinematic viscosity. Using parameters of the experimental boxes, the heat loss balance between convection and radiation at equilibrium was calculated. These calculations show that for the glass-covered box, radiation dominates the heat loss up to an air flow velocity of 1.5 m/s; it would be somewhat higher for a tilted plate.

Effect of scale on *h*

A full-scale greenhouse would obviously have a higher surface area A, but also a lower average value of h, since h is inversely related to the length of a plate:

$$h = \frac{kNu}{L} \tag{3}$$

However, in seeking to scale up the mathematical model to the size of a real greenhouse, we encounter computational difficulties, because at larger scales the Biot number and Reynolds number restrictions are exceeded, and the convection is turbulent. These issues compound the problem of modeling a full-scale greenhouse. But full-scale calculations would use the same methods as do such calculations for the heating and cooling of any building or large structure. There is an abundance of literature available to address this general engineering problem, which goes beyond the scope of this article. As mentioned earlier, the question of interest here is not a greenhouse *per se* but the mechanism of heating in the “greenhouse effect.”

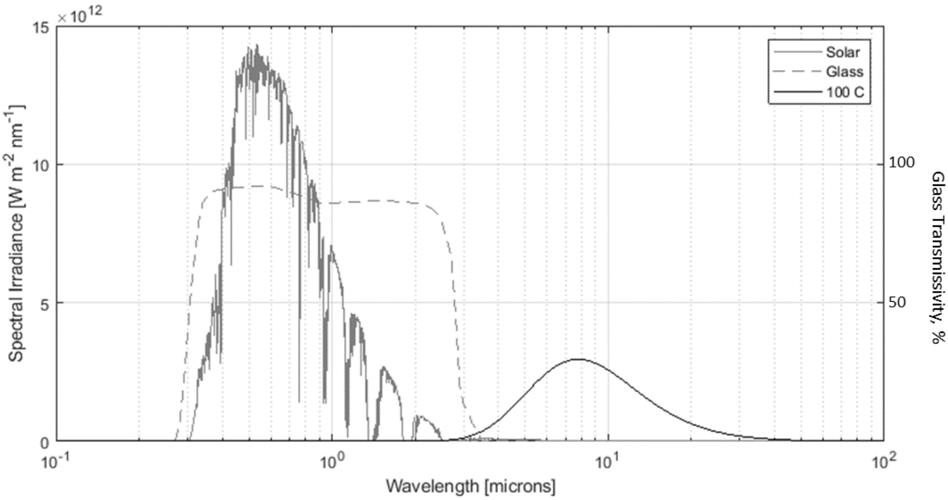

Figure 6: (a) Solar radiation at Earth's surface from [36], (b) transmissivity of window glass (right scale) from [37], (c) Planck blackbody radiation from internal plate at 100° C. (The blackbody radiation has been amplified by 10^5 to increase its visibility on the plot).

Radiation loss from the glass-covered box

Figure 6 shows the spectral data that are relevant to the discussion of radiation loss. Incoming solar radiation (a) is mostly transmitted through the glass (dashed curve (b)). But glass is opaque in the infrared, so the radiation from the internal black plate (c) is prevented from escaping. Infrared radiation from the plate heats the opaque glass, which radiates to the sky. As mentioned earlier, at equilibrium the measured temperature of the glass was about 42-47° C. This is much lower than that of the plate (about 100° C). In qualitative terms, the plate is partially "insulated" by the glass; its heat loss is reduced, so its temperature is higher. For the polyethylene-covered box, infrared radiation from the black plate goes directly to the sky. The plate in the glass-covered box cannot release this radiation, so it gets hotter.

Conclusion

Confusion about the "greenhouse effect" analogy still pervades even well-intentioned literature that seeks to provide an accurate explanation of the mechanism of climate change. Although most scientists are not climate change skeptics, there are numerous references to the "greenhouse effect" in which the author assumes that the greenhouse analogy is false (recalling Wood's article from 1909) but that the atmosphere is nevertheless heated by the mechanism of radiation trapping. This confusion has been propagated in textbooks [38, 39], in a NOAA tutorial [8], an ACS tutorial [9], an AIP tutorial [10], references on Wikipedia [40], and even in the congressional testimony of Carl Sagan [11].

The experimental and theoretical results shown in this article demonstrate that the "greenhouse effect" *is* a correct analogy to the atmosphere: both are heated primarily by radiation trapping. Full acceptance of this analogy by the science community is long overdue.

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