Climate change in a shoebox: Right result, wrong physics

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Classroom experiments that purport to demonstrate the role of carbon dioxide's far-infrared absorption in global climate change are more subtle than is commonly appreciated. We show, using both experimental results and theoretical analysis, that one such experiment demonstrates an entirely different phenomenon: The greater density of carbon dioxide compared to air reduces heat transfer by suppressing convective mixing with the ambient air. Other related experiments are subject to similar concerns. Argon, which has a density close to that of carbon dioxide but no infrared absorption, provides a valuable experimental control for separating radiative from convective effects. A simple analytical model for estimating the magnitude of the radiative greenhouse effect is presented, and the effect is shown to be very small for most tabletop experiments. © *2010 American Association of Physics Teachers.*

I. INTRODUCTION

The worldwide interest in climate change induced by the by-products of human activity presents opportunities and challenges to the physics teacher. A clear and compelling classroom demonstration of the basic physics by which atmospheric gases can change the steady-state temperature of the Earth's surface would be a powerful tool. Several such demonstrations have been described.[1–5] All involve comparing the temperature rise in a container filled with air with that of the same or a similar container filled with carbon dioxide when exposed to radiation from the Sun or a heat lamp. Typically, a larger temperature rise is observed with carbon dioxide and the difference is attributed, explicitly or implicitly, to the physical phenomena responsible for the climate change. We argue here that great care is required in interpreting these demonstrations and, in particular, that for the case of the demonstration described by Lueddecke *et al.*,[1] the results arise primarily from processes related to convective heat transport that plays no role in climate change. We demonstrate the value of using a third gas, such as argon, as an additional experimental control, and present a simple model that permits a quantitative estimate of the expected temperature rise due to the gas's infrared absorption.

Atmospheric greenhouse gases such as carbon dioxide can raise the temperature of the Earth's surface by absorbing some of the far-infrared radiation emitted by Earth and re-emitting it isotropically. Because the atmosphere is thin compared to the Earth's radius, roughly half of the re-emitted radiation is directed back toward the Earth's surface, effectively increasing the amount of incident radiant energy (radiative forcing). The temperature of the Earth must then rise until its thermal radiative output matches the increased radiative input. Although there is enormous complexity in the detail, the fundamental physics of the climate change is that of radiative energy transfer.[6–9]

We will refer to this mechanism as the "radiative greenhouse effect." It has been known for more than a century that the warming of air in a real greenhouse results primarily from entirely different physics—mainly that the glass prevents mixing between the warm air inside and the cooler air outside, and therefore suppresses convective heat transfer between the interior and the exterior; the infrared absorption of the glass plays a much smaller role.[9–12] We show here, via experimental data and a simple theoretical model, that the effects observed in the demonstration described in Ref. 1 arise from a similar restriction of convection rather than from radiative effects. In this case, it is the density difference between carbon dioxide and air, rather than the presence of a solid barrier, that suppresses mixing of the gases. Although the details differ, similar considerations apply to other demonstrations that have been reported.[2–5]

II. THE DEMONSTRATION

Our experiment, shown in Fig. 1, is modeled on Ref. 1. The key elements are a source of radiant power at visible and near-infrared wavelengths, representing the Sun; an absorbing surface, representing the Earth's surface; an atmosphere of variable composition; and a means of monitoring the temperature at or near the absorbing surface. Two identical plastic containers with open tops are each placed under 250 W heat lamps. In each container an electronic temperature probe is mounted 2.5 cm above the bottom and shielded from direct radiation from the lamp. The temperature is monitored as a function of time using a data logger.

After the lamps are turned on, the temperatures of the probes in both containers gradually increase until they reach a steady state at approximately 27.5 °C, an increase of about 5 °C above the ambient temperature. At $t \approx 500$ s, carbon dioxide at about 27 °C was added[13] to one container. As shown in Fig. 2, the temperature immediately began to rise, reaching a maximum of about 34.5 °C before beginning to drop. (The reason for the temperature drop at ≈ 1200 s is discussed in the following.) The dramatic temperature increase when CO_2 is added is consistent with that described in Refs. 1–5 and appears to give a compelling demonstration of the physics behind the effect of greenhouse gases on the
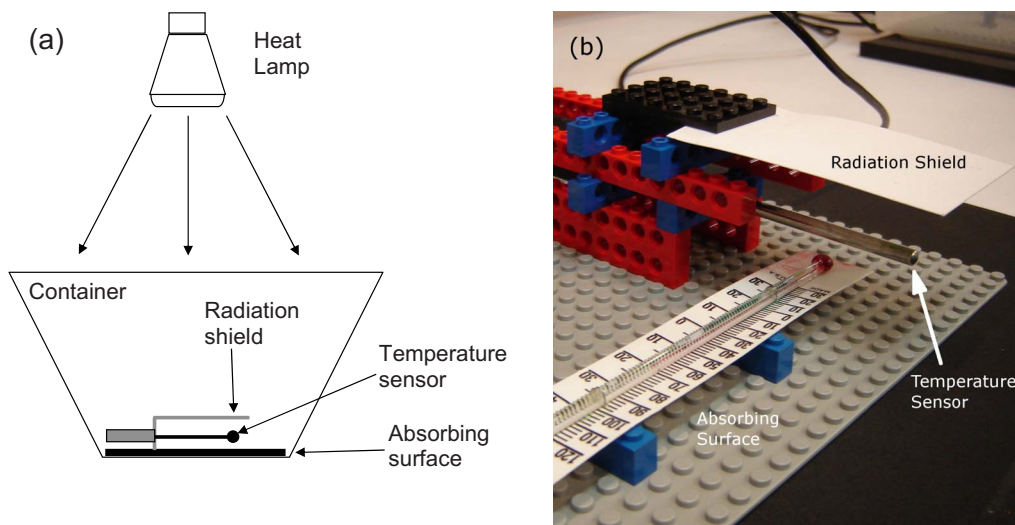
Fig. 1. (Color online) Experimental configuration. (a) Schematic diagram of the apparatus. (b) Photograph of the temperature sensor, absorber, and radiation shield assembly.

Earth's temperature. [One of us (R.G.T.) confesses to having used it for that purpose.] The demonstration is all the more striking because the change from air to CO_2 is invisible— nothing about the system appears to have changed, and yet the temperature rises. Moreover, it seems to be a well-controlled demonstration of the Earth's situation: The only thing that is changed is the addition of carbon dioxide to the "atmosphere."

Carbon dioxide differs from air in respects aside from its infrared absorption. In particular, CO_2 is denser than air (molecular mass of 44 u, compared to an average of 29 u for air). One consequence is that CO_2 remains in the container for some time even with the top open, as can be verified by lowering a lighted candle into the container. The higher density can affect the convective heat transfer between the gas in the container and the cooler ambient air. To determine whether the temperature rise when CO_2 is added is a result of
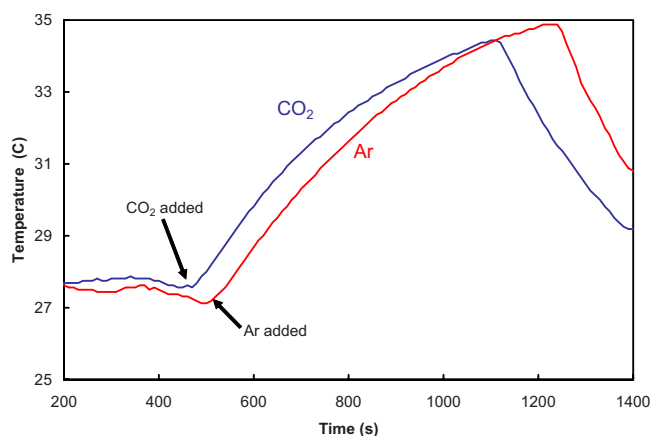

Fig. 2. (Color online) Temperature variation when the containers are filled with carbon dioxide and argon, as indicated, after steady state is reached in air. The heat lamps are on throughout the time shown. When either gas is added, at the times shown by the arrows, the temperature rises toward a new steady-state value before decreasing when the gas level drops below the level of the temperature sensor. The effects of the two gases are almost identical. Because argon does not absorb infrared radiation, the temperature increase must be due to other effects.

CO_2's infrared absorption rather than from density effects, we replicated the experiment in the second container using argon gas rather than carbon dioxide. Argon's mass (40 u) is close to that of CO_2, and thus its effect on the convective heat transport should be similar, but because it is a monatomic gas, it has no infrared absorption bands. Therefore, the radiative greenhouse effect does not occur for argon, and it represents a good experimental control for separating radiative and convective effects.

The curve labeled "Ar" in Fig. 2 shows the response when the second container was filled with argon. The temperature rose by approximately the same amount and at the same rate as for CO_2. Because Ar does not absorb infrared radiation, the temperature rise when Ar is added must be due to suppression of the convective heat transfer rather than to radiative effects, just as in the case of real greenhouses. We conclude that the experiment is a demonstration of a "greenhouse effect," but not of the radiative phenomena responsible for climate change.

A simple quantitative model shows that a temperature rise as large as we have observed when CO_2 is added cannot be accounted for by CO_2's infrared absorption, but can be readily explained by a suppression of convection. In our one-dimensional model of heat transfer, shown schematically in the inset in Fig. 3, the surface is represented as a flat black-body at the steady-state temperature T, exchanging energy with the ambient environment, which is represented as a blackbody at temperature T_a, by both radiation and convection. Radiant energy of intensity I_{lamp} is incident on the surface from the lamp, maintaining it at a slightly higher temperature than the ambient.

The rate of convective heat loss per unit area can be approximated as

$$I_{conv} = h\Delta T, \tag{1}$$

where $\Delta T = T - T_a$ and h is an empirical "film coefficient."[11] In the absence of atmospheric absorption, the net radiative energy flux outward from the surface to the room is given by
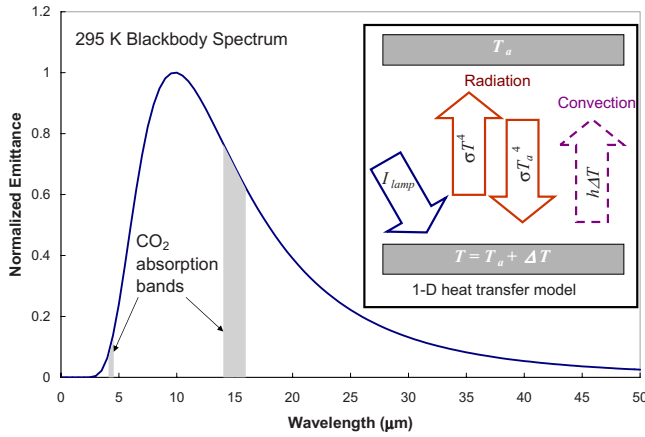
Fig. 3. (Color online) Normalized emission spectrum of a 295 K blackbody with the locations of the primary absorption bands of carbon dioxide shown. Inset: Schematic representation of the one-dimensional radiative transfer model discussed in the text.

$$I_{\text{rad}} = \sigma(T^4 - T_a^4) \approx 4\sigma T_a^3 \Delta T = g\Delta T, \qquad (2)$$

where σ is the Stefan–Boltzmann constant. This energy flux represents the difference between the outward flux radiated by the surface and the inward flux from the ambient environment (excluding the lamp). The relative magnitudes of the coefficients g and h characterize the relative importance of radiation and convection. For temperatures near room temperature, the radiative coefficient $g = 4\sigma T_a^3$ is approximately 6 W/m² K. Typical values of the convective coefficient h for a flat horizontal surface in air range from 4 to 20 W/m² K.[11]

In steady state the total energy flux away from the surface, $(h+g)\Delta T$, is equal to the incident intensity from the lamp, leading to the temperature rise

$$\Delta T_0 = \frac{I_{\text{lamp}}}{h_0 + g_0}, \qquad (3)$$

where the subscript "0" denotes the steady-state condition in air.

To examine the effect of replacing the air with carbon dioxide, we consider two limiting cases. First, following the assumption implicit in the interpretation of the demonstrations in Refs. 1–5, we assume that convective losses are unchanged, and the only effect of the carbon dioxide is to absorb a fraction f of the thermal (far-infrared) radiation to and from the surface. Because the surface and the environment have nearly the same temperature, the spectral distributions of these two fluxes are essentially the same, and thus f is the same for the fluxes in both directions. Half of the absorbed energy is then reradiated back in the direction from which it came, and hence the result is to reduce the net thermal energy flux, and thus the effective radiative coefficient g, by a factor of $(1 - f/2)$. The fractional change in the steady-state temperature rise above room temperature is given by

$$
\begin{aligned}
\frac{\Delta T - \Delta T_0}{\Delta T_0} = \frac{\delta(\Delta T)}{\Delta T_0} &= \frac{1}{\Delta T_0}\left(\frac{d(\Delta T)}{dg}\right)\delta g \\
&= -\frac{1}{\Delta T_0}\frac{I_{\text{lamp}}}{(h_0 + g_0)^2}\delta g \\
&= -\frac{1}{\Delta T_0}\left[\frac{\Delta T_0}{h_0 + g_0}\left(-g_0\frac{f}{2}\right)\right] = \frac{f}{2}\left(\frac{1}{1 + h_0/g_0}\right),
\end{aligned}
\qquad (4)
$$

provided that $f \ll 1$. If the only effect of replacing the air with CO_2 is to increase the infrared absorption, the fractional change in the temperature rise above ambient, relative to the increase with air alone, is at most $f/2$ for negligible convective transport ($h_0 = 0$) and is even smaller if convective transport is significant ($h_0 \approx g_0$ or greater).

The infrared absorption spectrum of CO_2 is dominated by two strong absorption bands from 4 to 4.5 μm and from 14 to 16 μm.[14,15] For both bands, a few centimeters of pure CO_2 gas is sufficient for nearly complete absorption.[15] It is straightforward to calculate f as

$$f = \frac{\displaystyle\int_{\substack{\text{absorption} \\ \text{bands}}} P(\lambda, T_a)d\lambda}{\displaystyle\int_0^\infty P(\lambda, T_a)d\lambda}, \qquad (5)$$

where $P(\lambda, T_a)$ is the Planck blackbody function at temperature T_a. Figure 3 shows the blackbody function for $T_a = 295$ K with the CO_2 absorption bands indicated. The ratio of the shaded areas to the total area under the curve represents f.

For $T_a = 295$ K, $f = 0.10$ and is dominated by the 14–16 μm band. This value of f means [see Eq. (4)] that adding carbon dioxide to the system should increase ΔT by approximately 5% from its original value. Before carbon dioxide was added, the temperature was about 5 °C above ambient. Therefore, the radiative greenhouse effect due to the addition of carbon dioxide should have increased the temperature by at most a few tenths of a degree. In reality, ΔT more than doubled when CO_2 was added, increasing by about 7°, too large an effect by at least a factor of 10 to be explained by a radiative mechanism.

In contrast, a model in which changes in radiative transfer are neglected, but the convective coefficient h is reduced effectively to zero by the introduction of a heavier gas (CO_2 or Ar), predicts a fractional change in the temperature rise above ambient of

$$\frac{\Delta T - \Delta T_0}{\Delta T_0} = \frac{h_0 + g_0}{g_0} - 1 = \frac{h_0}{g_0}, \qquad (6)$$

when air is replaced by the heavy gas.

In the experiment, $\Delta T \approx 2\Delta T_0$. This approximate doubling of ΔT observed in both CO_2 and Ar can be explained if the convective and radiative transfer coefficients in air are comparable, which we have shown is reasonable.

The observations that CO_2 and Ar gave almost identical results rule out a primarily radiative mechanism and strongly implicate convection. In addition to being consistent with these observations, our model shows that radiative effects are small and easily dominated by changes in convection, making it difficult to devise a convincing and authentic class-

room demonstration of the radiative greenhouse effect. Even if the experiments were done in a sealed container, and CO_2 were compared with Ar, differences in convective transport could not be ruled out.

The abrupt transition from gradual warming to rapid cooling in our experiment at about 1200 s (see Fig. 2) provides hints as to the actual nonradiative processes responsible for the temperature rise when either Ar or CO_2 is added. To determine the origin of the temperature decrease, we filled the first container with CO_2 again and checked the CO_2 level every few minutes by lowering a lighted candle into the container and observing the height at which it was extinguished. We found that the level dropped steadily, presumably due to slow diffusion of CO_2 out of the box. Using typical values of gas diffusion coefficients, we estimate a time of the order of hundreds of seconds for diffusion over a distance of several centimeters, roughly consistent with observation.[16]

Although the level of CO_2 decreased throughout the experiment, the temperature increased continuously and appeared to be smoothly approaching a steady-state value until the level of the gas dropped below the temperature sensor, at which time the gas abruptly began to cool. The suddenness of the transition suggests that the rate of heat transfer to the air outside the box is unrelated to the thickness of the Ar or CO_2 layer, but depends only on the presence of an interface between the dense gas and the lighter ambient air. Otherwise, the transition from heating to cooling would occur gradually, with no discontinuity of slope. It is likely that the suppression of gas mixing at the interface by the density difference is primarily responsible for the observed greenhouse effect in this demonstration, just as the suppression of mixing by the glass roof is primarily responsible for the warmth in a real greenhouse. Although convection in a two-component gas is not amenable to back-of-the-envelope calculations, we note that the difference in heat loss between still air and a gentle breeze is greater than a factor of 10 (Ref. 11). Thus, it is not unreasonable to suppose that suppressing interfacial mixing by replacing air with a heavier gas could reduce the convective coefficient h from a value comparable to the radiative coefficient g to a value much smaller than g—the conditions required to explain the approximate doubling of ΔT observed in our measurements.

In some of the reported demonstrations, the container is sealed so that interfacial mixing should not be a factor, but a temperature difference between air and CO_2 was still reported.[3–5] Sealing the container brings into play additional factors, which are difficult to quantify, especially the infrared characteristics of the "window." In Ref. 5, for example, ΔT is reported to be 25% greater for CO_2 than for air. As we have argued, a difference of this magnitude cannot be accounted for by far-infrared absorption. (This experiment probably involves the direct absorption of sunlight rather than of re-emitted far-infrared radiation, but that effect should be even smaller.[7]) Simple models of natural convection suggest that the difference in the heat flow between the two gases should be less than 10%.[17] The calculations depend on the geometry, however, and the conditions are in a transition regime between laminar and turbulent flow, and thus it is possible that small changes could have disproportionate effects. These uncertainties reinforce the value of including a comparison case that uses a heavy gas without infrared absorption, such as argon.

Our analysis does not in any way call into question the idea that increased CO_2 concentrations in the Earth's atmo-sphere can cause increases in the average temperature of the Earth's surface that, while small on an absolute scale, are large enough to have serious consequences. (A change in the mean surface temperature of 5 °C—the difference between our current climate and that of the last ice age—represents less than a 2% change in the absolute temperature.) The analysis of the radiative greenhouse effect for the Earth, even at its simplest, differs in important respects from the model we have presented. First, ambient thermal radiation incident on the Earth is negligible; in effect $T_a = 0$, and convective transport away from the Earth as a whole does not occur. As a result, Eqs. (2) and (3) are modified to

$$I_s = \sigma T_s^4, \tag{7a}$$

$$\Delta T_s = \frac{\Delta I}{4\sigma T_s^3}, \tag{7b}$$

where I_s is the average intensity of radiation arriving at the surface of the Earth, T_s is the average surface temperature, and ΔI is the change in the incident intensity due to the absorption and re-emission caused by the increase in the carbon dioxide concentration. Similar analyses have been given by Barker and Ross[9] and by Knox.[8]

Even without anthropogenic contributions there is enough CO_2 in the atmosphere such that radiation with wavelengths near the centers of the two absorption bands is already fully absorbed, so that changes in atmospheric CO_2 concentrations have little differential effect on atmospheric absorption at those wavelengths. The radiative effects of changes in atmospheric CO_2 arise from the tails of these bands and from other weaker absorption bands that are not fully saturated.[7,9] Calculating these effects requires detailed modeling of the carbon dioxide absorption spectrum and the atmosphere, but the basic physics involved is well understood.[7–9,18] The best current estimate is that changes in carbon dioxide concentration from preindustrial times to the present result in an increase in the incident radiative intensity of 1.7 W/m^2.[19] Equation (7b) then gives $\Delta T \approx 0.3$ °C. More realistic models must take into account feedback effects, such as an increase in albedo due to increased cloud cover and a decrease in albedo due to reduced ice and snow coverage, and many other effects, but even this simple model gives the correct order of magnitude.

III. CONCLUSION

Our results demonstrate that the temperature rise observed in a popular classroom demonstration[1] arises not from the radiative greenhouse effect responsible for global warming but primarily from the suppression of convective heat transport between CO_2 and air due to the density difference between the two. This density difference, much like the roof of a real greenhouse, suppresses gas mixing at the CO_2-air interface and therefore inhibits heat transfer. The magnitude of the radiative effect is more than an order of magnitude smaller and is difficult to demonstrate convincingly. The interpretation of other similar demonstrations[2–5] differs in detail, but is subject to the same considerations.

Our results apply only to the interpretation of classroom-scale demonstrations; they do not call into question the effects of anthropogenic greenhouse gases on the Earth's climate or existing models of those phenomena.

Although not an accurate demonstration of the physics of climate change, the experiment we have considered and related ones are valuable examples of the dangers of unintentional bias in science, the value of at least a rough quantitative prediction of the expected effect, the importance of considering alternative explanations, and the need for carefully designed experimental controls. Specifically, the use of argon as a test gas is an important supplement to the comparison of air and carbon dioxide because it allows effects due to the higher density of CO_2 to be separated from those related to its infrared absorption.

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