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The Greenhouse Effect and its Problems

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Introduction

The phrase greenhouse effect in the context of climate refers loosely to the assertion that since the earth’s atmosphere is relatively transparent to solar radiation, and relatively opaque in the infrared, due to the presence of substances which absorb in the infrared (the so called greenhouse gases: mainly water vapor and condensed water in the form of clouds, but also carbon dioxide, methane, nitrous oxide, and ozone), the surface temperature must be warmer than it would be in the absence of these greenhouse gases in order for surface cooling to balance incoming solar radiation. As evidence for this view, it is noted that the earth’s surface is, indeed warmer than it would be in the absence of an atmosphere. It is usually further claimed that an implication of this picture is that increasing greenhouse gas concentrations will increase surface temperatures. Figure 1 in IPCC 90 illustrates this view – focusing only on radiative heat exchange and inaccurately portraying even this case. This line of reasoning has a long history, dating back to Fourier and Arrhenius (1896) in the 19th Century.

There are, however, many reasons to question the hypothesis. Some basic arguments run as follows¹:

1. The basic greenhouse process is not simple. In particular, it is not simply a matter of the gases which absorb heat radiation (greenhouse gases) keeping

¹ A general view to the physics of climate may be found in Lindzen, 1994.
the earth warm. If it were, the natural greenhouse would be about 4 times more effective than it actually is. In reality, the surface of the earth is cooled by evaporation and motion systems which bodily carry heat both upwards and polewards, thus bypassing much of the atmosphere's greenhouse absorption. The actual greenhouse effect depends on these motions as well as the greenhouse gas concentrations above the levels where motions deposit heat and the details of the temperature distribution at these levels. All of these are matters of significant basic uncertainty, and involve errors in model behavior so large as to be discerned even in the uncertain data.

2. The most important greenhouse gas in the atmosphere is water vapor, and percentage changes in this gas are comparably important at all levels of the atmosphere (at least below 16 km) despite the fact that the concentration of water vapor is thousands of times less at 16 km than at the surface. Roughly speaking, changes in relative humidity on the order of 1.3-4% are equivalent to the effect of doubling CO$_2$. Our measurement uncertainty for trends in water vapor is in excess of 10%, and once again, model errors are known to substantially exceed measurement errors in a very systematic way. It should be added that the radiative effect of water vapor is nonlinear, and the effect of small changes in dry regions will matter much more to the radiative balance than changes in moist regions. It is the dry regions that have been most poorly measured.

3. The direct impact of doubling CO$_2$ on the earth's temperature is rather small: on the order of 0.3°C (Lindzen, 1995). Larger predictions depend on positive feedbacks, primarily from upper atmosphere temperature and from water vapor, acting in such a manner as to greatly magnify the effect of CO$_2$. Both these factors arise from models with errors in these factors, the importance of which is likely to greatly exceed the effect of doubling CO$_2$.

There is very little argument about the above points. They are, for the most part, textbook material, showing that there are errors and uncertainties in physical processes central to model predictions that are an order of magnitude greater than the climate forcing due to a putative doubling of CO$_2$. There is, nonetheless, argument over whether the above points mean that the predicted significant response to increased CO$_2$ is without meaningful basis. Here there is disagreement. Major users and developers of large models frequently defend model results regardless of the above. Theoreticians and data analysts are commonly more skeptical. The word, significant, should be emphasized. Global mean temperatures fluctuate by 0.25°C and more without anyone particularly noticing. It seems most peculiar that such disagreements should be described in terms of contrarians and consensi. In order to understand this,
one must turn to a major source of semantic confusion: namely the difference between a natural consensus arising in a field and a forged consensus. It should be added that there is a substantial body of both theoretical and observational analysis that strongly suggests that the models have exaggerated the impact of increasing CO₂. However, for present purposes it suffices to note that there is neither an observational basis for concerns nor a credible theoretical basis. Support for the popularly stated scenarios are, at this point, little more than statements of belief rather than science.

The consensus concerning the behavior of the observed globally averaged temperature is pretty much a natural consensus – it has increased about 0.45±0.15°C since the late 19th Century. So too is the consensus over the increase in CO₂: it appears to have increased from 280ppmv in 1800 to 360ppmv today. The consensus concerning the model response to increasing CO₂, however, is more a forged consensus. Boehmmer-Christiansen (1994) describes the issue.

The purpose of the present article is to examine the greenhouse hypothesis more carefully, and to present a more precise formulation in order to illustrate the underlying complexity of the hypothesis, and to examine real and potential weaknesses. Few topics have suffered more from over-simplification. In order to avoid this within the length limitations of this article, we make extensive use of references. In order to facilitate the use of these references, we cite specific figures.

**Thermal equilibrium for an earth without an atmosphere.**

The sun behaves approximately like a black body of radius, rₛ=6.599·10⁵ km, at a temperature of Tₛ=5783°K. The radiative flux at the sun’s surface is given by the expression σTₕ⁴, where σ is the Stefan-Boltzmann Constant (5.67032·10⁻⁸ Wm⁻²K⁻⁴). Flux refers to radiation per unit area. Thus, at the earth’s distance from the sun, rₑₛ=1.4960·10⁸ km this flux is reduced by the factor (rₛ/rₑₛ)². The earth’s disk has a cross-section, aₑₛ=πrₑsburg, where rₑₕ is the earth’s radius (6.378388·10³ km), and thus intercepts aₑₛ σTₛ⁴(rₛ/rₑₛ)² radiation from the sun. In order to balance this intercepted radiation, the earth would warm to a temperature Tₑ, where σTₑ⁴=4πrₑ²=aₑₛ σTₛ⁴(rₛ/rₑₛ)². This leads to a solution, Tₑ=272°K, which is surprisingly close to the current mean temperature of the earth, 288°K. Somewhat inconsistently, it is generally noted that clouds (which require the presence of an atmosphere) and other features of the earth reflect 31% of the incident radiation. Taking account of this reduces Tₑ to 255°K.
The radiative role of the atmosphere.

The spectral distribution of radiation of a black body is given by the Planck distribution which is given by

$$B\lambda(\theta) = \frac{2bc^2\lambda^{-5}}{e^{bc/k\lambda\theta} - 1}$$

where $h$ is the Planck constant ($6.626176 \times 10^{-34}$ Joule second), $c$ is the speed of light ($2.997924580 \times 10^5$ km s$^{-1}$), $\lambda$ is the wavelength, and $\theta$ is the absolute temperature in 'K. This will differ for bodies at $T_s=5783^\circ K$ and $T_e=255^\circ K$. The two distributions are illustrated in Figure 1a taken from Goody and Yung (1989). The spectra are well separated. Figures 1b and 1c from the same reference show the atmospheric absorption spectrum for the total atmosphere above the ground and for the atmosphere above 11 km. The latter height corresponds to a characteristic height of the tropopause. They show that there is relatively little absorption of visible light although gases like ozone, oxygen and nitrogen do absorb ultraviolet radiation primarily in the upper atmosphere. On the other hand the terrestrial radiation is primarily in the infrared where there is extensive absorption by water vapor with other gases like carbon dioxide, oxygen and methane contributing where water vapor absorption is weaker.

If the atmosphere cooled only by radiation, then each layer of the atmosphere would absorb infrared radiation, and emit radiation at that layer's temperature. Thus, for the surface to cool, it would have to be warmer than the air above, and similarly, each layer would have to be warmer than the air immediately above it. Temperature would decrease with height until the opacity of the air above was sufficiently small that radiation could begin to escape directly to space. In point of fact, the radiation to space is characterized by the atmospheric temperature at about one optical depth into the atmosphere (from the top). (An optical depth of 1 corresponds to the path over which radiation is attenuated by(1/e)=0.368.) Such a situation is illustrated in Figure 9.10 in Goody and Yung (1989). Such radiative equilibrium leads to surface temperatures of about 350°K which are very much warmer than what is observed. It should be noted that temperatures begin to increase with height above the tropopause because of the direct absorption of ultraviolet by ozone in the stratosphere and mesosphere. In reality the position at which optical depth = 1 depends on wavelength, but we shall ignore this for purposes of simplification.

As was noted long ago by Emden (1913), radiative equilibrium profiles are intrinsically impossible since they lead to such large decreases in temperature with height as to render the atmosphere unstable with respect to buoyant convection.
Figure 8.1. Atmospheric absorptions. (a) Black-body curves for solar emissions around 6000K and terrestrial emissions around 250K. (b) Atmospheric absorption spectrum for a solar beam reaching ground level. (c) The same for a beam reaching the temperate tropopause. The axes are chosen so that areas in (a) are proportional to radiant energy. Integrated over the earth's surface and over all solid angles, the solar and terrestrial fluxes are equal to each other; consequently the two black-body curves are drawn with equal areas. Conditions are typical of mid-latitudes and for a solar elevation of 40° or for a diffuse stream of terrestrial radiation. From Goody and Yung, 1989.

Convective adjustment.

In response to the above described problem, a simple fix was developed. The vertical temperature gradient in the troposphere was simply set to its observed mean value rather than any particular value one could associate with convection per se. Despite this, the procedure is still referred to as convective adjustment. The result of this fix is shown in in Möller and Manabe, 1961 (reproduced as Figure 6 in Lindzen, 1994). The surface temperature they obtain is now close to its observed average value of 288K. Of course, this is hardly a prediction. The vertical temperature profile was specifically chosen to match observations, while the latitude and associated solar insolation were chosen to replicate the observed mean temperature. What this simple result does do, however, is to highlight the fact that the surface of the earth, and for
that matter the lower layers of the atmosphere, do not cool primarily by radiation. Rather, atmospheric motions bodily carry heat upwards, and in a properly 3-dimensional world, polewards (Figure 7, Lindzen, 1994). A more accurate, though still one dimensional picture, is shown in Figure 1.3 in IPCC95 which shows that radiative cooling from the surface is largely canceled by infrared down-welling from the atmosphere. The largest source of net cooling is evaporation, and sensible heat transport is also important. (Sensible heat refers to heat per se as opposed to evaporation which is referred to as transport of latent heat since the heat is only realized when the vapor condenses.) The heat from the last two processes is carried into the atmosphere by both convective towers which carry heat upwards, and the large scale circulation which carries heat both upwards and polewards. The complexity of these motion systems makes it evident that 'convective adjustment' is both a gross oversimplification and a misnomer. Implicit in 'convective adjustment' is a sequence wherein radiation produces a convectively unstable profile which then breaks down convectively. If, however, one allows for a horizontal as well as a vertical dimension, then the horizontal variations in solar insolation automatically give rise to motion systems which lead to stable stratification which, in turn, potentially eliminates the need for simple buoyant convection. The exception is primarily in the tropics where the presence of moisture and its state changes lead to conditional instability which renders the system convectively unstable despite the fact that it would not be unstable in the absence of moisture. Nevertheless, the use of convective adjustment has, as we shall explain in the following section, important implications for the calculated response to increased greenhouse gases.

The role of vertical dynamic coupling in the response to perturbed greenhouse forcing.

Because of the presence of greenhouse gases, the emission temperature of the earth corresponds to some upper level temperature at approximately one optical depth into the atmosphere rather than the surface temperature. We shall call this level, \( z_e \). If one estimates the emission level from a typical General Circulation Model (GCM), one finds that the level varies with location but is typically near 500 mb (or 5.5 km). The particular level depends on the model water vapor distribution which is a matter of controversy. It is useful to consider the role of perturbed greenhouse gas concentrations from the perspective of emission levels. In Figure 8.2 we see the situation for an unperturbed atmosphere. Figure 8.3 shows the situation when one increases the amount of greenhouse gas: obviously, by increasing the total amount of infrared absorbing (or greenhouse) gas, one has elevated the level at which optical depth 1 occurs, and since temperature decreases with height at such levels, the emission temperature, \( T_e \), is now reduced (for a doubling of \( \text{CO}_2 \), the level is
moved upwards by about 50 m). Thus, the outgoing longwave radiation no longer balances the net incoming solar radiation. In order to restore equilibrium, the temperature at the new \( z_e \) must rise to the original emission temperature. The relation of the temperature change at the new \( z_e \) to temperature change at the surface is dependent on the dynamic coupling of the two levels. Thus, in Figure 8.4, we illustrate three different changes in temperature, each of which allows equilibration with space. In Figure 8.4a we simply hold the
temperature profile fixed while uniformly increasing temperature everywhere. As noted by Lindzen (1995), this approach leads to a very small temperature increase (0.3°K) associated with a doubling of CO₂. A problem with this approach is that the stratosphere, which is in approximate radiative equilibrium, must cool when CO₂ is increased. In Figure 8.4b, we allow for this, altering the tropospheric lapse rate in order to maintain continuity with the stratosphere. This leads to a much larger surface response. Of course, one could always achieve equilibrium by changing the temperature at zₑ without changing the surface temperature at all. This is illustrated in Figure 8.2c. Such a situation might account for the possibility of the earth responding differently to changes in solar output (which directly influence the surface) than to changes in greenhouse gases. In summary, the actual change expected at the surface depends critically on the nature of the dynamic vertical coupling in the troposphere. The use of convective adjustment assumes the coupling is rigid.

Vertical coupling in nature and models.

That there is an important measure of vertical independence in the thermal structure of the atmosphere is well known. Figure 1 in Lee and Mak (1994) demonstrates this very clearly. Patterns of variance in static stability are clearly different in the 900-700mb layer near the surface from what is found in the upper layer (500-300mb). This is also true in models. However, as Sun and

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2 If one insists on allowing both stratospheric cooling, and maintaining a constant unchanged lapse rate, then the response is more complicated, leading to a further elevation in zₑ and a larger response at the surface (typically on the order of 1.2°K).
Held (1996) demonstrate, there is greater vertical coherence in models than is observed—especially in certain regions. That is to say, in models temperature variations at upper levels in the atmosphere are more tightly coupled to temperature variations at the surface than is found in nature. Relationally, Held and Suarez (1974) found that OLR correlates far better with temperature at 500 mb than with temperature at the surface. This would, of course, be impossible if temperatures at the surface and at 500 mb (approximately 6 km above the surface) followed each other exactly. As we have shown above, excessive vertical coherence can also lead to excessive sensitivity to perturbations in greenhouse gases.

Feedbacks

By feedbacks, we generally refer to processes which are affected by surface temperature in such a way as to alter the response of the surface to some initial forcing. Although it is rarely referred to as a feedback, excessive vertical coherence in the temperature field may well constitute the largest positive feedback in current models. Note that such processes may be peculiar to models rather than to nature—in which case the model response may be spurious. Most commonly, the term feedbacks refers to processes which alter either the net incoming solar radiation or the amount of infrared absorbing gas. Thus changes in cloud and snow cover will change the former, while changes in cloud cover and water vapor will change the latter. In this connection, it is important to recall that the most important greenhouse gas in the atmosphere is water vapor. A measure of the importance of water vapor is given in Figure 1 of Lindzen (1997) where it is shown that changes in relative humidity of 5% will (all other things kept constant) alter OLR by from 2-5 W m⁻² depending on the relative humidity being perturbed with greater responses being associated with smaller unperturbed relative humidity. For purposes of comparison, doubling CO₂ decreases OLR by 4 W m⁻². It should be noted that water vapor at zₑ is very variable and measurements of relative humidity are generally uncertain to within at least 10%. Over most of the earth (especially in the tropics), air is subsiding at zₑ and frequently originates from thousands of kilometers away (Sun and Lindzen, 1993). This should be contrasted with the air near the surface. The air in the lowest 2 km forms a turbulent boundary layer where the air is well mixed and tightly coupled to the surface; here, warming is indeed associated with increased water vapor. However, the air above the boundary layer has an entirely different origin. Nonetheless, in current GCMs water vapor is tightly coupled in the vertical (i.e., variations in water vapor above the boundary layer closely follow variations in the boundary layer), so that warming inevitably leads in these models to an increase in humidity at all
levels and a positive feedback which turns out to be essential to all predictions of significant warming. However, as Sun and Held (1996) show in their Figure 5, such tight coupling is far from what is observed. This is extremely important for predicted responses to increased anthropogenic greenhouse gases. That there is substantial disagreement between model and observed water vapor is shown in Spencer and Braswell (1997), Bates and Jackson (1997), and Schmetz and van de Berg (1994). Recall that the characteristic discrepancies of 20% in relative humidity are equivalent to discrepancies of 10-20 Wm$^{-2}$ in flux. The common assertion that a warmer world will involve more evaporation and hence greater humidity is patently false. Evaporation is balanced by precipitation. Thus, in principle, all increase in evaporation could go directly into precipitation without altering the humidity of the air. The moisturization of the air depends in part on the efficiency of precipitation, with more efficiency associated with less moisturization. In general, precipitation efficiency increases with temperature (Rogers and Yau, 1989).

An approximate expression for the response in terms of feedbacks is

$$\text{radiative effect with feedbacks} = \frac{\text{radiative effect without feedbacks}}{1 - \sum \phi_i}$$

where the $\phi_i$'s are the various feedback factors. Characteristic feedback factors estimated for GCMs are 0.41 for water vapor, 0.2 for clouds, and 0.1 for snow-ice albedo. The water feedback is clearly the most important, and without it no model will produce a large response to doubled CO$_2$. All the feedbacks are highly uncertain even with respect to sign. The water vapor feedback was first
described explicitly by Manabe and Weatherald (1967) who posited a fixed relative humidity so that warming would be accompanied by increased specific humidity everywhere. Current atmospheric observations offer no support for the assumption of fixed relative humidity at levels above the surface boundary layer.

Further complexity

The above discussion focuses primarily on a simple one dimensional picture of the world. Even this picture is substantially more complex and subtle than one might suppose. However, the real world is not one dimensional. As Spencer and Braswell (1997) show, water vapor varies dramatically with horizontal position, with very dry regions adjacent to extremely moist regions (see also Figure 3 in Lindzen, 1997). Most radiative cooling comes from dry regions which have low, warm emission levels. In practice, the actual greenhouse effect depends significantly on the relative areas of moist and dry regions rather than the areal mean humidity. The same applies to the water vapor feedback.

Conclusion

We have seen that a proper description of the greenhouse effect does not predict that surface warming must inevitably result in increasing levels of greenhouse gases leading to surface warming. Moreover, we see that model predictions of significant warming are highly dependent on feedbacks in the models whose physical basis is tenuous at best. One may reasonably conclude that current GCMs are inadequate for the purpose of convincingly determining whether the small changes in radiative fluxes at the top of the atmosphere associated with an increase in CO$_2$ are capable of producing significant climate change. However, we may not be dependent on uncertain models in order to ascertain climate sensitivity. Observations can potentially directly and indirectly be used to evaluate climate sensitivity to forcing of the sort produced by increasing CO$_2$ even without improved GCMs. The observations needed for direct assessment are, indeed, observations that we are currently capable of making, and it is possible that the necessary observations may already be in hand, though the accuracy requirements may be greater than current data provides. Still, the importance of the question suggests that such avenues be adequately explored. Since the feedbacks involved in climate sensitivity are atmospheric, they are associated with short time scales. Oceanic delays are irrelevant since observed surface temperatures are forcing the flux changes we are concerned with. The needed length of record must be
determined empirically. This is discussed in greater detail in Lindzen (1997). Indirect estimates, based on response to volcanos, suggest sensitivity may be as small as 0.3–0.5°C for a doubling of CO₂ which is well within the range of natural variability (Lindzen and Giannitsis, 1998). This is not to suggest that such change cannot be detected; rather, it is a statement that the anticipated change is well within the range of what the earth regularly deals with.

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