TAKING GREENHOUSE WARMING SERIOUSLY

by

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1. INTRODUCTION

In science, there is an art to simplifying complex problems so that they can be meaningfully analyzed. If one oversimplifies, the analysis is meaningless. If one doesn't simplify, then one often cannot proceed with the analysis. When it comes to global warming due to the greenhouse effect, it is clear that many approaches are highly oversimplified. This includes the simple 'blanket' picture of the greenhouse effect shown in Figure 1. We will approach the issue more seriously in order to see whether one can reach reasonably rigorous conclusions. It turns out that one can.

In Section 2, we present a physically correct view of the greenhouse effect, and show how this view enables us to use modeling results and observations in order to estimate a bound on the greenhouse contribution to recent surface warming of about 1/3. This is, indeed, somewhat less than the iconic claim in the IPCC Summary for Policymakers of Working Group 1 which claimed that it was likely that most of the recent warming was due to man. The present estimate is more constrained, and thereby suggests a lower climate sensitivity than is commonly found in current models. Section 3 discusses the origin of the contradicted claim as well as its relation to claims of high climate sensitivity. It turns out that far more than the iconic claim is needed for the sensitivity required for alarm. The main point of this paper is simply to illustrate why serious and persistent doubts remain concerning the danger of anthropogenic global warming despite the frequent claims that 'the science is settled.'

2. THE CLIMATE GREENHOUSE EFFECT

In Figure 1 (taken from a popular exhibit at the National Academy's Koshland Museum) we see a common depiction of the greenhouse effect. It is generally recognized to be oversimplified, but defended on the grounds that the general public would not be able to follow the correct treatment. The idea is that sunlight is primarily in the visible portion of the spectrum due to the high emission temperature of the sun (about 6000° K) while the radiation from the earth is in the infrared portion due to its lower emission temperature (about 255° K). Greenhouse gases are those substances that are reasonably transparent in the visible but capable of absorbing and emitting in the infrared. The 'emitting' part, though conveniently ignored in some oversimplified treatments, will turn out to be very important. In any event, the oversimplified argument then proceeds as follows. Part of the sunlight reaching the earth is reflected by clouds, and the earth's surface. The remainder (Net Incoming Solar Radiation) warms the earth and this warming is balanced by the earth's infrared (or thermal)

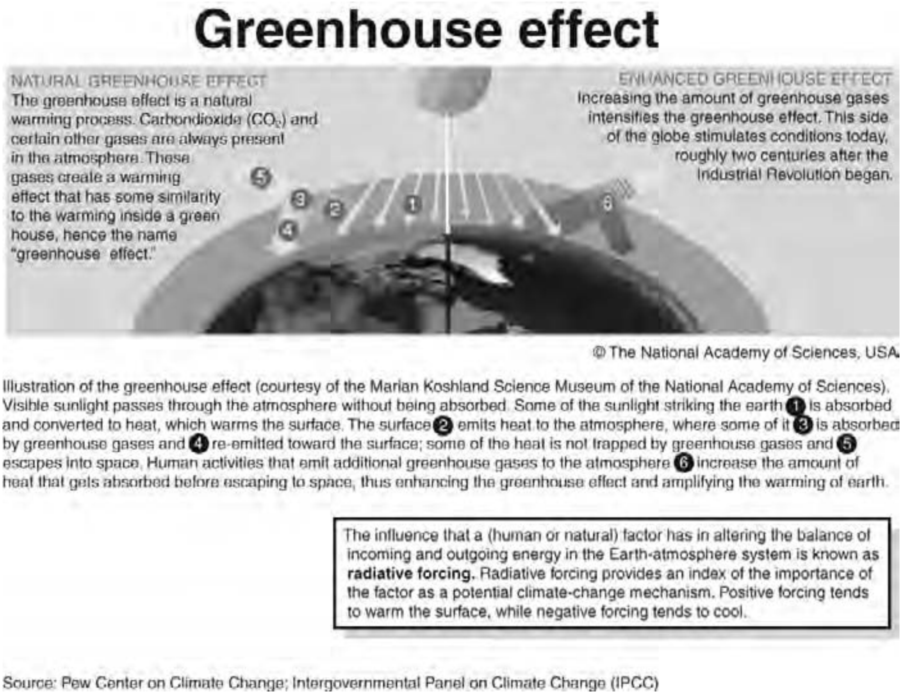

Figure 1: Oversimplified depiction of the greenhouse effect.

radiation. However, the presence of greenhouse substances (the most important of which are water vapor and clouds) inhibits this cooling by thermal radiation, and serves as a blanket which causes the earth to be warmer than it otherwise would be. It is commonly claimed that the natural component of this blanket keeps the earth about 33° C warmer than it would be in the absence of this blanket. The claim is a little inappropriate insofar as it requires getting rid of the greenhouse impact of clouds while retaining them to reflect sunlight. Getting rid of clouds as reflectors would reduce this difference substantially. This, however, is a relatively minor point. The general idea proposed in the oversimplified treatments is that adding man made greenhouse gases to those naturally present will cause the temperature to increase further. The doubling of CO_2 is used as a benchmark for estimating the sensitivity of climate to such increases. It is generally acknowledged that simply doubling CO_2 should lead to a warming of about 1° C. However, in current models, the natural greenhouse substances (water vapor and clouds) act in such a manner as to greatly amplify this warming. This is referred to as positive feedback.

There is something very seriously wrong with this oversimplified picture. Namely, the surface of the earth does not cool primarily by thermal radiation. The situation is more nearly akin to the schematic shown in Figure 2. The main greenhouse gas, water vapor, generally maximizes at the surface in the tropics and sharply decreases with

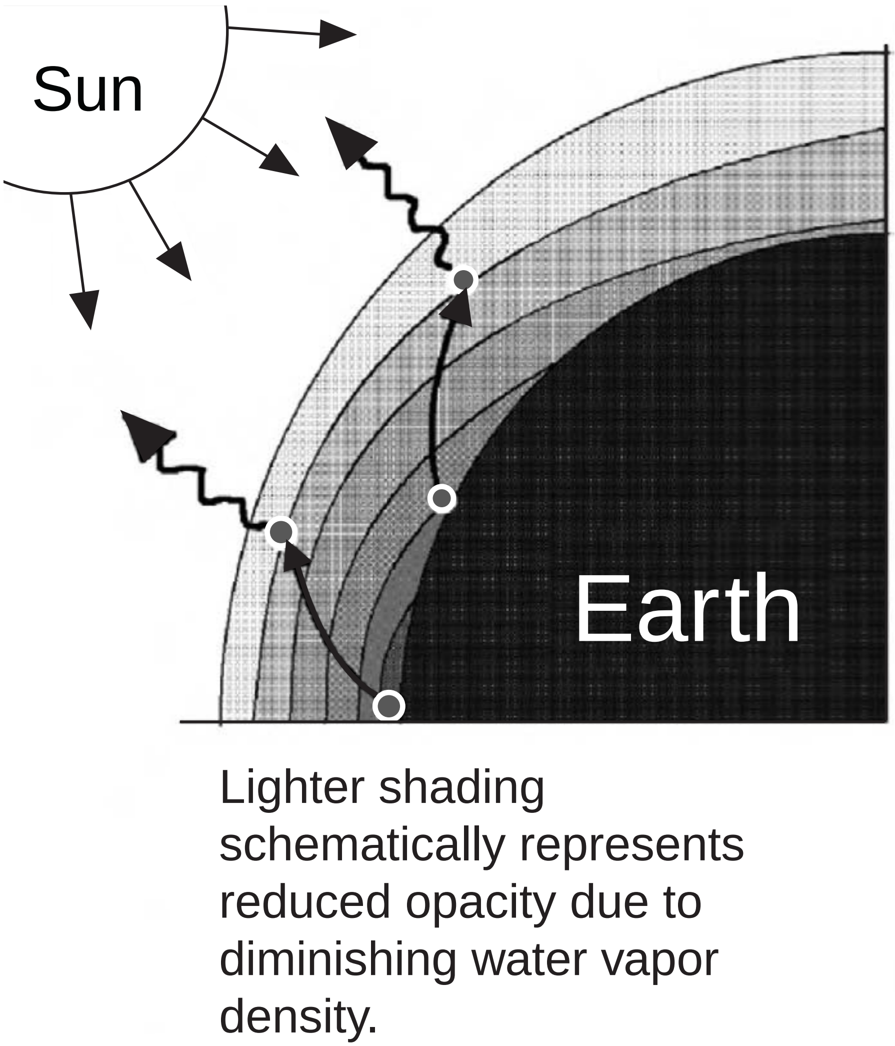

Figure 2: More realistic depiction of how the earth's surface cools.
(From Lindzen, 1990.)

both altitude and latitude. There is so much greenhouse opacity immediately above the ground that the surface cannot effectively cool by the emission of thermal radiation. Instead, heat is carried away from the surface by fluid motions ranging from the cumulonimbus towers of the tropics to the weather and planetary scale waves of the extratropics. These motions carry the heat upward and poleward to levels where it is possible for thermal radiation emitted from these levels to escape to space. We will refer to this level (which varies with the amount of water vapor at any given location) as the characteristic emission level. Crudely speaking, the emission from this level is

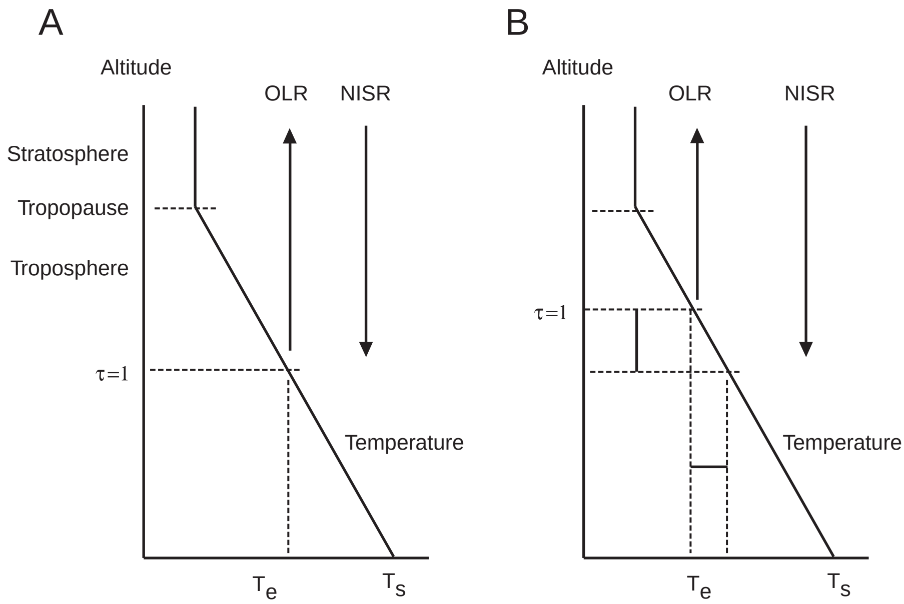

Figure 3: Schematic depiction of how greenhouse effect actually works.
(From Lindzen, 1995.)

proportional to the 4th power of the temperature at this level. Figure 3a offers a simplified one dimensional picture of the situation. Largely because of the motions of the atmosphere, the temperature decreases with altitude to some level known as the tropopause. The height of the tropopause varies with latitude. In the tropics, the tropopause height is about 16 km. Near 30° latitude, the tropopause height drops to about 12 km, and near the poles it is around 8 km. Below the tropopause, we have what is called the troposphere. The characteristic emission level is referred to as $\tau = 1$. τ is a non-dimensional measure of infrared absorption measured from the top of the atmosphere looking down. Crudely speaking, radiation is attenuated as $e^{-\tau}$. The level at which $\tau = 1$, is one optical depth into the atmosphere, and radiation emitted from this level is proportional to the 4th power of the temperature at this new level. When the earth is in radiative balance with space, the net incoming solar radiation is balanced by the outgoing longwave radiation (OLR or thermal radiation or infrared radiation; these are all commonly used and equivalent terms) from the characteristic emission level, $\tau = 1$. When greenhouse gases are added to the atmosphere, the level at which $\tau = 1$ is raised in altitude, and, because the temperature of the atmosphere decreases with altitude (at the rate of approximately 6.5° C per kilometer), the new characteristic emission level is colder than the previous level.

This situation is illustrated in Figure 3b. Because $\tau = 1$ is now at a colder level, the outgoing longwave radiation no longer balances the net incoming solar radiation,

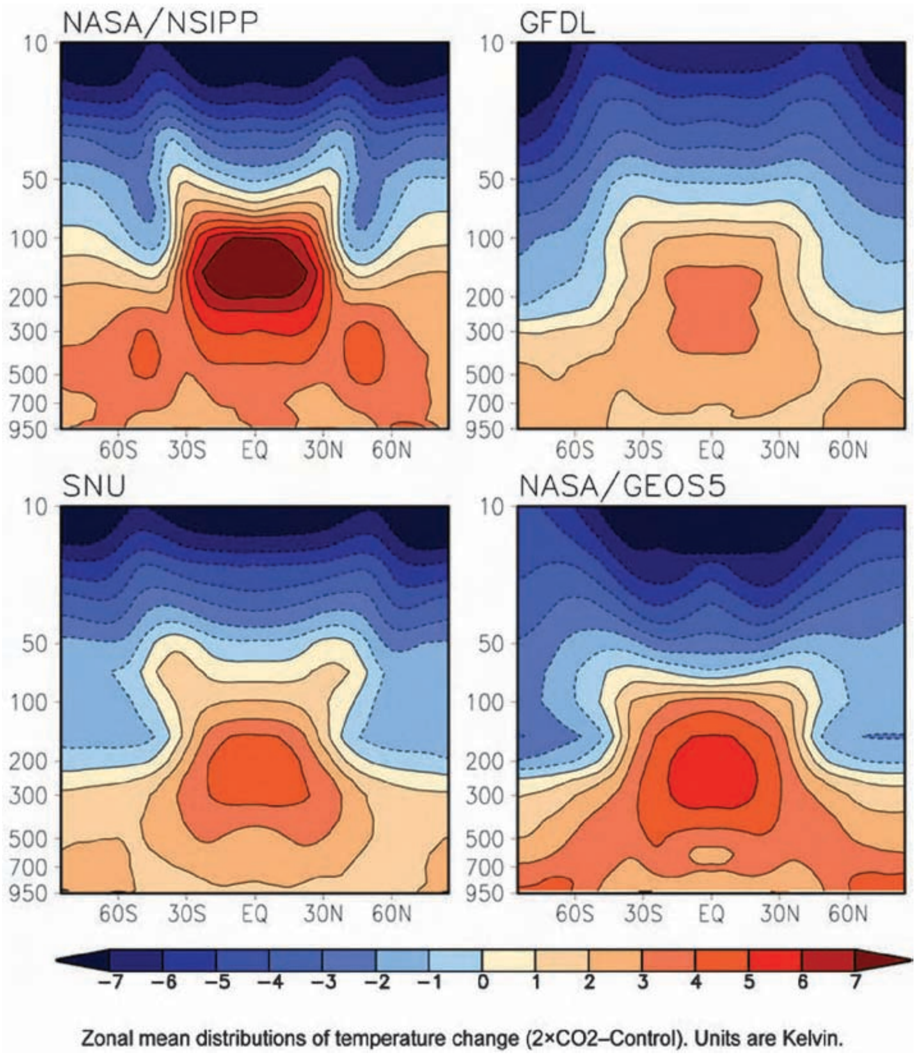

Figure 4: Zonally averaged, equilibrated temperature change associated with doubling CO_2 as a function of latitude and pressure for four different GCMs. (From Lee et al., 2007.)

and the earth is no longer in thermal balance with space; this imbalance is what we refer to as the *radiative forcing*. In order to reestablish balance, the temperature at the new $\tau = 1$ level must increase to about the temperature that had existed at the initial $\tau = 1$ level. In practice, the $\tau = 1$ level is typically in the neighborhood of 7–8 km in the tropics and at lower levels in the extratropics. It is the warming at $\tau = 1$ that is the fundamental warming associated with the climate greenhouse effect (to distinguish it from plant greenhouse which operates in a very different manner).

How warming at the $\tau = 1$ level relates to warming at the surface is not altogether clear. It is at this point that models prove helpful. Figure 4 shows how temperature changes when CO_2 is doubled in 4 rather different General Circulation Models (Lee et al., 2007). The runs shown differ from those that were run for the IPCC in that the models were simplified to isolate the effects of CO_2 forcing and climate feedbacks. Also the models were run until equilibrium was established rather than run in a transient mode in order to simulate the past. Thus, they isolate greenhouse warming from other things that might be going on (the transient situation will be discussed later). What is shown is the temperature averaged around a latitude circle as a function of latitude and height. Following common meteorological practice, height is replaced by pressure level. Pressure decreases approximately exponentially with height. 100 hPa (hecto Pascals) corresponds roughly to 16 km; 200 hPa to 12 km; 500 hPa to 6 km; and 1000 hPa to the surface. What we see is that warming is strongly peaked in the tropical troposphere near the $\tau = 1$ level (which actually differs from model to model because the amount of water vapor differs among the models). Roughly speaking, the warming at $\tau = 1$ in the tropics is from more than twice to about three times larger than near the surface regardless of the sensitivity of the particular model. This is, in fact, the signature (or fingerprint) of greenhouse warming. Stated somewhat differently, if we observe warming in the tropical upper troposphere, then the greenhouse contribution to warming at the surface should be between less than half and one third the warming seen in the upper troposphere. Fortunately, we have been measuring atmospheric temperatures with balloons since at least the 1960's and with microwave satellite sensors since 1979. Initially, the satellite and balloon data were showing insignificant temperature change for the tropical troposphere, while surface data was showing a warming trend of about 0.13° C/decade. This gave rise to deep concern resulting in studies by both the National Research Council (2000) and the US Climate Change Science Program (2006) where strong attempts were made to find warming in the troposphere. It is now believed that there is indeed warming in the atmosphere. Figure 5 is the most recent depiction of the trends based balloon data from the United Kingdom's Hadley Centre and incorporating the adjustments suggested by the above studies. We see that the trend in the troposphere does have a relative maximum near 300 hPa of about .1° C per decade, and judging from the results in Figure 5, this should be associated with a surface trend of between 0.033 and somewhat less than 0.05° per decade. *Contrary to the iconic statement of the latest IPCC Summary for Policymakers, this is only on the order of a third of the observed trend at the surface, and suggests a warming of about 0.4° over a century. It should be added that this is a bound more than an estimate*. Greenhouse warming must appear in the neighborhood of 300 hPa, but warming at 300 hPa does not have to be greenhouse warming. Note that our inferences from Figure 5 support the objections of Essex and McKitrick (2002) and Essex et al., (2007) to the use of globally averaged temperature. Had we used globally averaged temperatures, it would have been almost impossible to correctly relate the underlying physics to the observations. It must also be recognized that a one-dimensional picture of the greenhouse effect, as illustrated in Figure 3, is not equivalent to a global average.

The above is a bound on climate sensitivity based on basic theory, observations and modeling studies. The modeling studies establish that the ratio of upper tropospheric

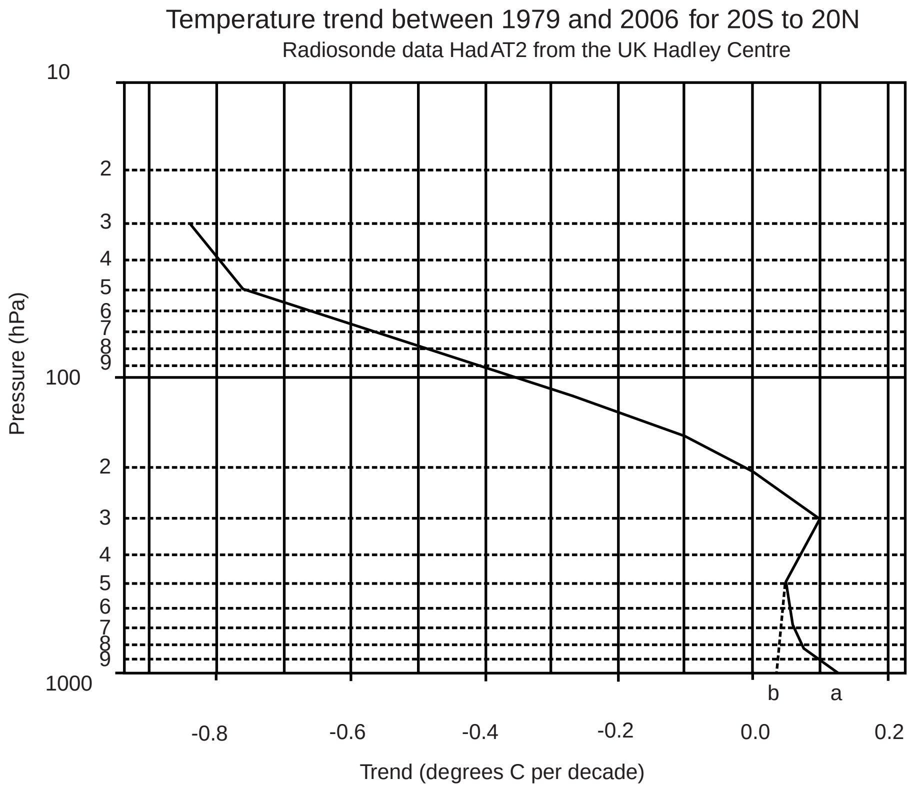

Figure 5: Temperature trend as a function of pressure level for period 1979–2006 in the tropics (20S-20N) based on balloon data analyzed by the Hadley Centre. ‘a’ shows the observed trend at the surface. ‘b’ shows that part of the surface trend that can be attributed to greenhouse warming.

tropical warming to surface warming is approximately 2.5:1 regardless of the model sensitivity. The bound does not depend on any specific feedback mechanism, but it does imply that strong positive feedbacks in current models are either wrong or more than balanced by negative feedbacks missing from these models. The alternative is that the observations are incorrect. The initial estimates from balloon radiosonde data showed no significant warming trend during the period (National Research Council, 2000). However, significant errors were found in the later report that led to the results shown in Figure 5. Given, the emphasis on errors leading to positive warming trend, it is intuitively unlikely that further errors will lead to much greater warming, though the possibility cannot, of course, be ruled out. However, judging from figure 10 of Thorne et al (2005) a reasonable error bar for the temperature trend would be ±0.07 C/decade (2 times the standard deviation). Thus, it is possible that the upper tropospheric tropical trend might be as large as 0.17 C/decade, implying a contribution of 0.068 C/decade to the surface trend – still only about half. It is also possible that there are errors in the surface trend that might lead to reducing that trend, but such a reduction would, of course, also still lead to reduced estimates of climate sensitivity. The modeling results, which avoid dependence on the uncertain feedbacks, seem remarkably robust.

Finally, it should be noted that the above argument is not significantly altered when considering transient situations. Indeed, given that greenhouse warming is initiated at the $\tau = 1$ level, and communicated to the surface (which is subject to 'ocean delay'), one would expect the imbalance to be greater in the transient, unequilibrated cases. Similarly, if the source of surface warming were at the surface (as would be the case for forcing by solar variability or ocean fluctuations), and there were feedbacks associated with greenhouse warming (for example the water vapor feedback), the amplification due to the feedback should occur first at the $\tau = 1$ level, and its communication to the surface would also be subject to 'ocean delay.' In such cases, the absence of relatively greater warming at $\tau = 1$ would suggest the absence of positive feedbacks and potentially the presence of negative feedbacks.

Note that the amplification of the warming signal with altitude shown in the model results might be partly due to the tendency of temperatures in the tropical free troposphere (ie, the part of the troposphere above the trade wind boundary layer which extends to about 2 km altitude) to follow what is known as the moist adiabat, but that does not alter any of the above arguments. It simply identifies an important part of the physics involved in relating the temperature at $\tau =1$ to that at the surface.

3. DEFENSE OF ANTHROPOGENIC CAUSALITY

How then did the recent IPCC Summary for Policymakers reach its conclusion that most of the surface warming over the past 30 years is due to anthropogenic forcing? The answer is that the modelers could not find anything else that could account for recent warming. The specific response of Alan Thorpe, head of NERC, the primary funding agency for climate research in the UK, is revealing:

> *"The size of the recently observed global warming, over a few decades, is significantly greater than the natural variations in long simulations with climate models (if carbon dioxide is kept at pre-industrial levels). Only if the human input of greenhouse gases is included does the simulated climate agree with what has been recently observed. Measurements prior to the modern instrumented record are probably insuficiently frequent and detailed to say whether such a global warming over a few decades has occurred before. However in any case, the real issue is whether human activity is causing the current warming because, if so, then we are able to do something about it.*
>
> *Climate models attempt to include all the natural factors that might lead to significant climate variations on the time scales of interest, i.e. years to decades to centuries. Clearly factors currently unknown to science can't be included, but we have no reason to suppose they exist."*[1]

[1]Thorpe's quote was taken from the NERC web site http://www.nerc.ac.uk/about/consult/debate/debate.aspx?did=1&pg=1. The arguments are the same as those presented in Chapter 12 of the IPCC WG1 Third Assessment Report (2001). They are also presented in Manabe et al., 2002. However, Thorpe's remarks are more consise.

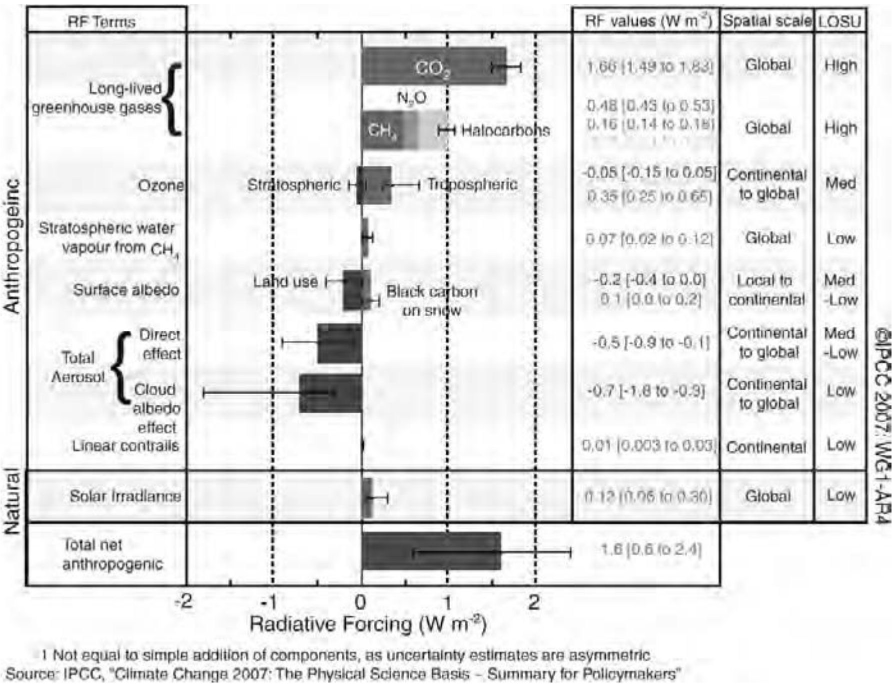

Figure 6: Current radiative forcing from anthropogenic sources. From IPCC WG1 Summary for Policymakers, 2007. RF refers to radiative forcing while LOSU refers to Level of Scientific Understanding.

Several features of this response should be noted immediately:

1. Evidence for natural variability is restricted to model outputs.
2. Evidence is said to include the irrelevant claim that only by assuming human causality is policy relevance assured. To be sure, policy relevance is important, but it cannot be a reason for a scientific conclusion.
3. The assertion that there is no reason to suppose that there are factors omitted from the models is likely to be false as we shall discuss shortly. So too is the claim that such factors are currently unknown to science.

Before proceeding to a discussion of item 3, it will be helpful to consider an interesting feature of what has become the iconic claim of the Summary for Policymakers. Figure 6, taken from the Summary for Policymakers, lists all the current sources of anthropogenic forcing used in current models, as well as the estimated magnitude of their contribution to the radiative forcing (in units of watts per square meter). For reference purposes, the radiative forcing associated with a doubling of CO_2 is about 3.5 watts per square meter (as noted in the last 3 IPCC

Scientific Assessments). The first three items in Figure 6 represent the main sources of anthropogenic greenhouse forcing. They are also the most accurately known of the anthropogenic forcings. Adding them up gives us a radiative forcing of about 3 watts per square meter, which is about 86% of the radiative forcing associated with a doubling of CO_2. That is to say we are almost at the radiative forcing associated with the benchmark of doubled CO_2. For the models used for Figure 4, we see that a doubling of CO_2 leads to surface warming of from about 1.5–3.5° K (or C). By contrast, the observed warming over the past century or so amounts to only about 0.6–0.8° C (not all of which need be due to increased greenhouse gases). On the face of it, this would seem to confirm that current models are much too sensitive to anthropogenic greenhouse forcing, assuming that all the observed warming was due to increasing greenhouse gases. Moreover, we have already shown that such warming actually accounts for only a half or less of the observed warming.

How then, can it be claimed that models are replicating the observed warming? Two matters are invoked. First, observe in Figure 6, that once one goes beyond the first three items, the terms are essentially unknown as illustrated by the large error bars (viz Anderson et al., 2003 and Schwartz et al., 2007, for aerosols). Indeed, a recent paper by Ramanathan et al., (2007) suggests that the warming effect of aerosols may dominate – implying that the sign of the aerosol effect is in question.

Thus, they can be used to essentially arbitrarily cancel half the anthropogenic greenhouse forcing (or more) as seen in the last item in Figure 6. This would still leave us with more warming than is observed. The second factor arises from a possibly important difference between the model runs used to simulate past climate and those used for Figure 4. The results in Figure 4 were arrived at by running the models to steady equilibria, while the simulations were time dependent runs that were stopped at the time corresponding to the last observation of temperature used for the comparison. In these transient runs, it takes time for the surface to respond to the forcing because the ocean takes time to respond, and the atmospheric transport tends to tie the land and ocean areas together. The ocean delay is proportional to both the climate sensitivity and the assumed thermal diffusivity of the oceans (Hansen et al., 1985; Lindzen and Giannitsis, 1998)[2]. In other words, excessive sensitivity of the models would contribute to the delay. It is also the case that current models often assume excessive thermal diffusivity (Willis et al., 2004; Schmitt et al., 2005; Merrifield, 2005). Despite this, it was still necessary to arbitrarily remove half the anthropogenic greenhouse forcing. The need to cling to the high sensitivities is readily explained by Thorpe's insistence on policy relevance. Without high sensitivity, this would be greatly diminished. Indeed, to maintain the ominous projections, it is necessary to assume that the aerosol cancellation will soon disappear (Wigley and Raper, 2002). However, these arguments are only possible if one chooses to ignore the fact that observations are

[2]Although it would be inappropriate to repeat a full analysis here, the reasons for this behavior are not hard to explain. Climate sensitivity is essentially a ratio of a change in temperature to a radiative forcing. In a sensitive climate, a large temperature is associated with a small forcing. The forcing, however, determines the *rate* at which the ocean temperature changes. For a given temperature change, this rate will be smaller the more sensitive the climate. The thermal diffusivity determines how deeply the heat must penetrate. The higher the diffusivity, the deeper the ocean layer that needs to be heated.

failing to display the distribution of warming that is associated with greenhouse warming.

This brings us to the last item: namely, is there really no reason to suppose that excluded processes exist? There are, in fact, numerous phenomena that current models fail to replicate at anywhere near the magnitudes observed. These range from the Intraseasonal Oscillations of the tropics (sometimes referred to as the Madden-Julian Oscillation, and having time scales on the order of 40–60 days) to El Niño (involving time scales of several years) to the Quasi-biennial Oscillation of the tropical stratosphere to the longer time scale phenomena like the Little Ice Age and the Medieval Warm Period (involving centuries). Under the circumstances, it seems reasonable to suppose that some things must exist that account for these model failures. For at least El Niño, we are pretty sure that the phenomenon involves the fact that the oceans are never in equilibrium with the surface. Irregular exchanges of heat between the deep abyssal waters and the near surface thermocline regions imply that the oceans serve as large sources and sinks of heat for the atmosphere, and these exchanges take place over time scales from months to centuries or longer. A very recent paper (Tsonis et al., 2007) suggests, in fact, that the surface temperature record can be accounted for by essentially superpositions of known oceanic fluctuations such as the Pacific Decadal Oscillations and the Atlantic Multidecadal Oscillations. There is, in fact, no reason to suppose current models are treating such matters adequately. Indeed, a recent paper from the Hadley Centre acknowledges this (Smith et al, 2007).

The above examples merely show that current models fail to describe many known climate changes, and that, therefore, the models' failure to account for the recent warming (largely confined to the period 1976–1995) hardly requires the invocation of anthropogenic forcing. It is nonetheless commonly argued by modelers that coupled models (even with passive mixed layer oceans) do adequately portray natural unforced variability (Manabe et al., 2002) despite acknowledging the cited shortcomings, and it may be reasonably claimed this contention is the fundamental assumption behind the iconic claim of the last IPCC WG1 SPM.

The failures cited do not *per se* deal with the matter of climate sensitivity. However, there is ample evidence that current models are indeed exaggerating climate sensitivity. The fact that so little of recent observed warming can be attributed to greenhouse warming may be a sign of this. Moreover, specific mechanisms have been identified such as the iris effect (Lindzen et al., 2000, Spencer et al., 2007) which is based on observations that current models fail to replicate. This effect should, if correct, provide a powerful negative feedback. As mentioned earlier, ocean delay is itself proportional to climate sensitivity, and the work of Lindzen and Giannitsis (1998) and Douglass et al., (2006) strongly suggested that the observed delay time is too short to allow large sensitivities.

On the other hand, it has been argued by Hansen (2005) that observed changes in ocean temperature (Levitus, 2005) implied model sensitivity was correct. While there are significant difficulties with Hansen's analysis – most notably that it assumes that the ocean is slave to the atmosphere on the time scales examined as well as with Hansen's interpretation (Lindzen, 2002), it remains of interest that more recent data suggests no statistically significant ocean warming (Gouretski and Koltermann, 2007); not surprisingly, this too has been contested albeit somewhat ambiguously (AchatRao et al., 2007).

4. CONCLUDING REMARKS

Using basic theory, modeling results and observations, we can reasonably bound the anthropogenic contributions to surface warming since 1979 to a third of the observed warming, leading to a climate sensitivity too small to offer any significant measure of alarm–assuming current observed surface and tropospheric trends and model depictions of greenhouse warming are correct. The virtue of the approach presented is that it offers critical testable points for assessing the argument. We next showed that the defense of the attribution of recent warming to man involves an observed warming that is smaller than expected, and where the attribution, itself, depends on relatively subjective claims concerning the ability of current models to accurately portray natural unforced climate variability. Thus, the claim that models cannot account for recent warming without external forcing is held to imply the role of human forcing. To be sure, current models can simulate the recent trend in surface temperature, but only by invoking largely unknown properties of aerosols and ocean delay in order to cancel most of the greenhouse warming (Schwartz et al., 2007). Finally, we note substantial corroborating work showing low climate sensitivity.

Ultimately, however, one must recognize how small the difference is between the estimation that the anthropogenic contribution to recent surface warming is on the order of 1/3, and the iconic claim that it is likely that the human contribution is more that 1/2. Alarm, we see, actually demands much more that the iconic statement itself. It requires that greenhouse warming actually be larger than what has been observed, that about half of it be cancelled by essentially unknown aerosols, and that the aerosols soon disappear. Alarm does not stem directly from the iconic claim, but rather from the uncertainty in the claim, which lumps together greenhouse gas additions and the cancelling aerosol contributions (assuming that they indeed cancel warming), and suggests that the sum is responsible for more than half of the observed surface warming. What this paper attempts to do is point the way to a simple, physically sound approach to reducing uncertainty and establishing estimates of climate sensitivity that are focused and testable. Such an approach would seem to be more comfortable for science than the current emphasis on models testing models, large ranges of persistent uncertainty, and reliance on alleged consensus. Hopefully, this paper has also clarified why significant doubt persists concerning the remarkably politicized issue of global warming alarm.

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