GLOBAL WARMING: WHAT WE KNOW AND WHAT WE DON'T KNOW.

RICHARD S. LINDZEN

Center for Meteorology and Physical Oceanography
Massachusetts Institute of Technology
Cambridge, MA 02139 USA

INTRODUCTION

Given normal climate variability, we may reasonably expect that there will be future climates both warmer and colder than the present regime. This, however, hardly supports the current fear that increasing greenhouse gases in the atmosphere will lead to catastrophic warming. The IPCC Scientific Assessment\(^b\) as well as the current update (Houghton, et al\(^a\)) both recognize that temperature changes over the past century (a net warming of $0.45^\circ C \pm 0.15^\circ C$) are consistent with natural variability and smaller than what would be expected for models predicting over about $1.3^\circ C$ equilibrium warming for a doubling of CO\(_2\) — assuming all the change over the past century were due to CO\(_2\). This, of course, seems unlikely since the bulk of the warming occurred before 1940. The update suggests that the expected warming was

\(^a\) The present paper is a slightly updated version of a paper that will appear in *Environmental Pollution*.

\(^b\) IPCC refers to the Intergovernmental Panel on Climate Change. This panel is sponsored by the UN's World Meteorological Organization and the UN Environmental Program. The panel consists in members posted by governments. University scientists tend to be very underrepresented — if only because most such scientists have neither the time nor the funds to participate.
to some extent cancelled by cooling resulting from cloud brightening by sulfates. The update, therefore, suggests that the past record might be consistent with an equilibrium response to CO$_2$ doubling of almost 2°C. While this is also not a catastrophically large warming, the IPCC estimate is based on the work of Charlson, et al$^3$ (1992) which probably overestimates sulfate loading by a factor of 3-4 (Seinfeld$^4$). Kiehl and Briegleb$^5$ have further shown that errors in radiation calculations lead to an additional reduction by a factor of about 3. We are, therefore, sticking with the 'uncorrected' value of 1.3°C from the original IPCC Scientific Assessment. It is worth noting that the Policymakers Summary of the IPCC Update suggests that observations are broadly consistent with predictions of significant warming. This statement, however, is essentially meaningless since it is equally true for a prediction of no warming from increasing CO$_2$. Thus, the data neither suggest nor provide support for current warming scenarios. Neither do simple greenhouse considerations. All other factors remaining constant, the equilibrium greenhouse warming, resulting from a doubling of CO$_2$, is estimated to be between 0.5°C and 1.2°C (Ramanathan$^6$, Lindzen, et al$^7$, Sun and Lindzen$^8$, Houghton, et al$^9$). These values may seem small, but CO$_2$ is only a minor greenhouse gas. If all CO$_2$ were removed from the atmosphere, water vapor and clouds would still provide the vast bulk of the present greenhouse effect (the global mean temperature is reduced by about 1.5°C). Predictions of larger equilibrium warming depend crucially on positive feedbacks from water vapor, cloud cover, and surface albedo (due to snowcover). Of these model feedbacks, water vapor is by far the largest. As it turns out, the physics of the water vapor budget is largely absent in current models. Indeed, in most (if not all) models the water vapor feedback is readily identifiable with a calculational error. Thus, there is also no theoretical basis for the predictions of larger warming than that which would be caused directly by increasing CO$_2$. Indeed, there are reasons to believe the feedbacks are negative, suggesting the equilibrium response to CO$_2$ doubling may well be much smaller than the direct response (Sun and Lindzen$^{8,9}$). Finally, the term 'equilibrium' should be explained. It refers to the response achieved over an infinite time. In point of fact, the actual response time (largely determined by heat transport into the ocean) increases proportionally to the expected equilibrium response (Hansen, et al$^{10}$, 1985). In fact, a model predicting a 4.8°C equilibrium warming for a doubling of CO$_2$ would only have reached 2/3 of this warming in about 160 years. It is interesting, in this regard, to note that the models examined in the IPCC Scientific Assessment produce warming by 2100 almost equal to the equilibrium response of these models to a doubling of CO$_2$, in these models, however, effective CO$_2$ has quadrupled by 2100. Had it only doubled, the predicted
Figure 1. Time dependent warming since 1880 for models with equilibrium responses of globally averaged surface temperature to doubling of CO₂ of 3.6°C and 4.8°C. Results are shown for CO₂ scenarios wherein CO₂ quadruples by 2100 and where it simply doubles by 2100. The quantity, ‘g’, refers to the equilibrium gain of the climate model where an unamplified response to a doubling of CO₂ is taken to be 1.2°C.

warming would have been much less. This is illustrated in Figure 1 where I show the expected warming for models with equilibrium responses to a doubling of CO₂ of 3.6°C and 4.8°C. Such models are at the very high end of the expected responses given by Houghton, et al\textsuperscript{12}. Results are shown for scenarios where CO₂ either doubles or quadruples by 2100 (and remains constant thereafter). We will expand on some of these points in the remainder of this paper.
SOME GENERAL CONSIDERATIONS

It is essential to separate two issues in discussing the issue of global warming. The first is the issue of external radiative forcing. By external radiative forcing, I mean sources of radiative forcing that are associated with matters that are specified externally to the climate system itself. Examples are radiative forcing produced by minor greenhouse gases resulting from man's activities, volcanically produced dust veils, solar variability, sulfate layers, orbital variations, etc. The second issue is that of climate response to external radiative forcing. These are distinctly separate issues. However, most discussions of global warming, by failing to separate these issues, contribute significantly to popular confusion. Although most of my discussion will focus on the issue of climate response, a brief discussion of the first issue may prove helpful.

EXTERNAL RADIATIVE FORCING

A doubling of atmospheric CO₂ will add about 2 watts/meter² to the Earth's surface heat flux. This is an approximately 1% alteration, and is far smaller than current model discrepancies in this quantity (Randall, et al¹¹). With some effort, it is possible to obtain estimates of other sources of forcing which appear competitive at this low level (Charlson, et al³ for sulfate layers, Penner, et al¹² for soot). Solar fluctuations of this magnitude cannot be completely ruled out. (Volcanic effects are far larger, but shortlived. We will return to the issue of volcanic effects later in this paper.) Thus far, almost all attention has been devoted to what I call homogeneous radiative forcing. By this, I mean radiative forcing applied relatively uniformly to the whole earth. Interesting in this regard is the response of the climate to orbital variations. These changes are associated with the major glaciation cycles of the last 700,000 years (Imbrie and Imbrie¹³, 1980). This is referred to as the Milankovitch mechanism. Orbital variations include variations in obliquity (associated with periods of about 40,000 years), precession of the equinoxes (associated with periods of about 20,000 years), and variations in orbital eccentricity (associated with periods of about 100,000 years). It is estimated that the first two may be associated with fluctuations in globally averaged insolation at the 1% level, but the third is associated with much smaller fluctuations in globally averaged insolation. Nevertheless, the climatic response is dominated by the third factor. This calls into question the whole notion of simple climate sensitivity. What appears to be at issue is the fact that while Milankovitch forcing produces only small changes in the annually averaged global insolation, it produces major changes in the seasonal and regional distribution of insolation. Such inhomogeneous changes can have profound effects on the dynamical heat fluxes from the tropics to the higher latitudes (Lindzen and Pan¹⁴). It is worth
noting that without such dynamical fluxes, the annually averaged equator-to-pole temperature difference would be about 100°C. Currently, the value is about 40°C. During very warm climates, it has been as low a 19°C, while during major glaciations, it has been as large as 60°C. Such changes call for major changes in the equator-to-pole heat flux. If one restricts attention to the tropics, the change in the heat flux corresponds to a change in the tropical heat budget more than an order of magnitude greater than that anticipated for a doubling of CO₂. The fact that the equator seems to have remained within a degree or so of its present temperature despite such changes is indicative of the stability of tropical temperatures. Extrapolation to the anticipated changes in CO₂ suggests warming on the order of a few tenths of a degree C, which would be essentially undetectable. Current models suggest *equatorial* warming of 2-4°C for a doubling of CO₂.

Indeed, major climate changes in the earth's history have always been associated with changes in the temperature difference between the tropics and high latitudes; tropical temperatures have remained almost invariant (Fairbridge¹⁵, Hoffert and Covey¹⁶). This at least suggests that it is inhomogeneities in radiative forcing that are important; simple radiative forcing (due to increasing CO₂ for example) provides relatively little inhomogeneity. Indeed, if there are physical reasons for the stability of tropical surface temperatures, then homogeneous forcing is unlikely to produce significant changes in global mean temperature (Lindzen¹⁷). Climate response to inhomogeneous forcing has received little attention so far. We will return to this point at the end of this paper. The issue is also discussed at greater length in Lindzen¹⁸.

Our present concerns about climate change center on the effects of increasing CO₂. Before turning to the issue of climate response, it may be worth considering briefly an aspect of this issue that is almost always taken as a given: namely, that CO₂ will inevitably increase to values double and even quadruple present values. Figure 2 shows the behavior of CO₂ since about 1800. Before 1958, the record is based on the analysis of ice cores. After 1958, it is based on direct atmospheric sampling. Clearly, CO₂ has been increasing. Prior to 1800 the density was about 275 ppmv (parts per million by volume). Today it is about 355 ppmv. The increase is generally believed to be due to the combination of increased burning of fossil fuels and (mostly before 1905) to deforestation. The total source is estimated to have been increasing exponentially with a characteristic time of 45 years — at least until 1973. From 1973 until 1990 the rate of increase may have been slower. About half the production of CO₂ has appeared in the atmosphere.
Figure 2. Atmospheric CO$_2$ increase in the past 250 years, as indicated by measurements on air trapped in ice from Siple Station, Antarctica (squares) and by direct atmospheric measurements at Mauna Loa, Hawaii (triangles). (From *Climate Change, The IPCC Scientific Assessment*, 1990.)

Predicting what will happen to CO$_2$ over the next century is a rather uncertain matter. By assuming a shift toward coal, advances in the third world's standard of living, large population increases, complete tropical deforestation, and limitation of nuclear and other non fossil fuels, one can generate an emissions scenario which will lead to an effective doubling of CO$_2$ by 2030 — if one uses a particular model for the atmospheric response to CO$_2$ emissions. This was referred to as the 'business as usual' scenario by the Intergovernmental Panel on Climate Change Working Group I (Houghton, et al$^1$). As it turns out, the carbon models used were inconsistent with the past century's record; they would have predicted that we would already have more than about 380 ppmv$^c$. An improved model developed at the Max Planck Gesellschaft

---

$^c$ The point is simply that most current carbon models have a chemical response time of about 200 years which implies a resident fraction of about 0.8. The resident
in Hamburg shows the so called 'business as usual' scenario does not even double CO₂ by the year 2100 (Heimann\textsuperscript{19}). As we see from Figure 3, their

\begin{figure}
\centering
\includegraphics[width=\textwidth]{CO2_Scenarios}
\caption{Expected CO₂ in the atmosphere according to various emissions scenarios. (From Heimann\textsuperscript{19})}
\end{figure}

fraction observed over the past century (approximately 0.5) is consistent with a response time equal to the e-folding time for emissions (about 45 years over the past century). In order to match the past century, ad hoc adjustments are made, but these adjustments are not generally applied to predictions (Keeling, D., personal communication).
model shows that under other scenarios, we may not even get much more CO\textsubscript{2} than is already in the atmosphere. Personally speaking, it seems unlikely that the indefinite future of energy belongs to coal. I also find it difficult to believe that technology won't lead to improved nuclear reactors within 50 years. As the IPCC update (Houghton, et al\textsuperscript{2}) notes, scenarios are not predictions. Given our present crystal ball technology, predictions for 50-100 years are more than anyone would rationally attempt.

Nevertheless, we have already seen a significant increase in CO\textsubscript{2} which has been accompanied by increases in other minor greenhouse gases as well (methane, chlorofluorocarbons, etc.). Indeed, in terms of greenhouse potential, we have had the equivalent of a 50\% increase in CO\textsubscript{2} over the past century (Hansen, et al\textsuperscript{20}). The effects of these increases are certainly worth studying — quite independent of any uncertain future scenarios. Similarly, given past trends, it is not at all unreasonable to expect substantial increases in CO\textsubscript{2}. The remainder of this paper will focus on the basis for the expectation that significant warming will accompany these changes in atmospheric composition.

CLIMATE RESPONSE

At the heart of current treatments of the climate response to increasing minor infrared absorbing gases is the so-called greenhouse effect (see Essex\textsuperscript{21} for a cogent critique of this terminology). Figure 4 shows the common popular presentation of the greenhouse effect. The crude idea is that the atmosphere is transparent to sunlight (apart from the very significant reflectivity of both clouds and the surface) which heats the Earth's surface. The surface attempts to balance this heating by radiating in the infrared. The infrared radiation increases with increasing surface temperature, and the temperature adjusts until balance is achieved. If the atmosphere were also transparent to infrared radiation, then the infrared radiation produced by an average surface temperature of -18\(^\circ\)C would balance the incoming solar radiation (less that amount reflected back to space by clouds, etc.). However, the atmosphere is not transparent in the infrared, and so the Earth must heat up somewhat more in order to deliver the same flux of infrared radiation to space. This is what is called the greenhouse effect. The fact that the Earth's average surface temperature is 15\(^\circ\)C rather than -18\(^\circ\)C is attributed to this effect\textsuperscript{d}. The main absorbers of infrared in the

\textsuperscript{d} It is interesting to note that these estimates of the greenhouse effect assume that we can remove water vapor and clouds (insofar as they absorb in the infrared) while retaining clouds to reflect sunlight. If we were to also assume that in the absence of water vapor there would be no clouds, then the resulting temperature would be 15\(^\circ\)C
Figure 4. Simplified schematic of the greenhouse warming process. (From Houghton, et al)

atmosphere are water vapor and clouds. As already noted, even if all other greenhouse gases (like carbon dioxide and methane) were to disappear, we would still be left with the bulk of the current greenhouse effect. Nevertheless, it is presumed that increases in carbon dioxide and other minor greenhouse gases will lead to significant increases in temperature. As we have seen, CO₂ is increasing. So are other minor greenhouse gases. A widely held, but (as we have seen) questionable, cooler than at present. Such a temperature would certainly allow the continuation of life. However, the greenhouse gases, water vapor and CO₂, are essential to life as we know it.
contention is that these increases will continue along the path they have followed for the past century.

It is worth noting immediately that the simple picture of the greenhouse mechanism is seriously oversimplified. Many of us were taught in elementary school that heat is transported by radiation, convection, and conduction. The above picture only refers to radiative transfer. As it turns out, if there were only radiative heat transfer, the greenhouse effect would warm the Earth to about 77°C rather than to 15°C. In fact, the greenhouse effect is only about 25% of what it would be in a pure radiative situation (Lindzen\textsuperscript{22}). The reason for this is the presence of convection (heat transport by air motions), which bypasses much of the radiative absorption. What is really going on is schematically illustrated in Figure 5. The surface of the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{schematic}
\caption{Schematic illustration of the role of dynamic heat transport in modifying greenhouse warming.}
\end{figure}

Infrared opacity is greatest at the ground over the tropics, and diminishes as one goes poleward and upward. Air currents bodily carry heat to regions of diminished infrared opacity where the heat is radiated to space -- balancing absorbed sunlight.
Earth is cooled in large measure by air currents (in various forms including deep clouds) which carry heat upward and poleward. One consequence of this picture is that it is the greenhouse gases well above the Earth's surface that are of primary importance in determining the temperature of the Earth. This is especially important for water vapor whose density decreases by about a factor of 1000 between the surface and 10 km. Another consequence is that one cannot even calculate the temperature of the Earth without models that accurately reproduce the motions of the atmosphere. Indeed, present models have large errors here (order 50%, Stone and Risbey\textsuperscript{23}, Geleyn, et al\textsuperscript{24}), and, not surprisingly, these models are unable to correctly calculate either the present average temperature of the Earth or the equator-pole temperature distribution. Rather, the models are adjusted (or 'tuned') to get these quantities approximately right.

Having said all this, it is still of interest to ask what we would expect a doubling of CO\textsubscript{2} to actually do. As already noted, if this is all that happened, we might expect a warming of from 0.5-1.2°C. The general consensus is that such warming would present few if any problems. However, the climate is a complex system where it is impossible for all other factors to remain constant. In present models, these other factors (commonly referred to as feedbacks) act as destabilizing factors which amplify the effects of increasing CO\textsubscript{2}, leading to predictions of warming in the neighborhood of 4-5°C. The most important of these factors in current climate models is due to water vapor. In all current models, upper tropospheric (3-12 km) water vapor, the major greenhouse gas, increases as surface temperatures increase. Without this feedback, no current model would predict warming in excess of 1.7°C — regardless of any other feedback (Arking\textsuperscript{25}). Unfortunately, the way these factors (like clouds and water vapor) are handled in present models is disturbingly arbitrary. In many instances the underlying physics is simply not known. In other instances there are identifiable errors. Even computational errors play a major role. For example, existing models have only 10-20 levels in the vertical, which is inadequate for predicting the behavior of a substance like water vapor which varies immensely with height. The difficulty leads to model predictions of negative water vapor in some parts of the atmosphere. The arbitrary filling routines used to correct this obviously unrealistic behavior play a major role in the model water vapor budgets (Rasch and Williamson\textsuperscript{26}). In fact, there is compelling evidence for all the known destabilizing feedbacks in the models to actually be stabilizing (negative) feedbacks. In that case, we would expect the response to CO\textsubscript{2} doubling alone to be diminished. The following paragraphs discuss this matter a bit further.

The issue of deep clouds (cumulonimbus towers) and water vapor is rather technical; it is also crucial to the issue. These towers are the main mechanism for surface air to communicate with the interior atmosphere. Moist air rises in these towers. As this air rises to levels of lower pressure, it expands and cools (as does
refrigerator coolant). As air cools, its capacity to hold water vapor diminishes. The excess water vapor condenses into liquid water or ice (depending on the temperature). In the simplest models of cumulonimbus towers, all the condensed vapor falls out as rain. When the cloud reaches its top altitude (in this simple model), it merges into the atmosphere as saturated (100% relative humidity) air at the cloud top temperature. I had noted (Lindzen, 1990\textsuperscript{22,27}) that as the surface warmed, cloud air would be more buoyant, and would reach higher top levels where the air would be colder and thus hold less water vapor. Hence, the supply of water vapor to the interior atmosphere would be diminished in a warmer climate. However, since water vapor is the main greenhouse gas in the atmosphere, this reduction would act to restrain the warming — i.e., provide a negative feedback. We then undertook two studies to check these ideas. In the first, we used some data showing the descent of the mountain snowlines during the last major glacial period (18,000 years ago, Broecker and Denton\textsuperscript{28}) to see whether the colder atmosphere of those times had more water vapor (Sun and Lindzen\textsuperscript{8}). Our study showed that it probably did, thus supporting the notion of a negative feedback. Our first study did not, however, tell us what mechanism was actually responsible for the negative feedback. Our second study undertook to examine the atmosphere's water vapor budget in greater detail (Sun and Lindzen\textsuperscript{9}). Here we confirmed that our original mechanism had a significant problem (This had been noted by Betts\textsuperscript{29}). An upper level source of water vapor would demand that relative humidity decrease rapidly downward which is not observed. The problem, it turned out, was our assumption that all condensed water vapor in the cloud fell out as rain. Significant amounts are, in fact, carried aloft in the cloud and thrown out into the atmosphere mainly as ice crystals (leading to extensive cirrus cloud cover). The main source of water vapor for the atmosphere proves to be falling droplets and ice crystals which reevaporate into the environment. What causes a cloud to loft more water substance is not totally well known, but it appears to be related (not surprisingly) to how fast cloud air is rising. Our first study did, in fact, show why cloud air would rise faster in a colder climate. As concerns current climate models, none of them take account of any of these issues.
Figure 6. Globally averaged temperature departures from the mean as a function of time from 1964 to 1990 at the 1000, 850, 700, 500, and 300 mb levels. Also shown are the time histories for globally averaged specific humidity departures from the mean at the same levels. Note that the mean specific humidity at 1000 mb is about 10 g/kg, while at 300 mb it is about 0.1 g/kg. (Oort, 1992, private communication; see also Oort, 1993)
These results would appear to be in conflict with recent studies purporting to ‘prove’ positive water vapor feedback on the basis of satellite observations\(^6\) (Raval and Ramanathan\(^{30}\), Rind, et al\(^{31}\)). There are many serious problems with both these papers (Minschwaner and McElroy\(^{32}\), Sun and Lindzen\(^{9}\)); however, both share one problem which is fatal. They both assume that water vapor above the turbulent surface layer (approximately the bottom 2 kilometers) is uniquely determined by surface temperatures immediately below. They, therefore, take local surface temperatures determined by geography and season as surrogates for climate. Unfortunately, over the bulk of the atmosphere (99.9% in the tropics, Sarachik\(^{33}\)) air is gently subsiding in order to compensate the rapid ascent in the active cumulus towers (which occupy about 0.1% of the area). Thus the air above the surface layer is decoupled from the surface immediately below. An appropriate observational test would consist in comparing the time histories of both globally averaged temperature and of globally averaged specific humidity (i.e., water vapor density) in the upper troposphere (above 2-3 km or, in meteorological parlance, 800-700 mb). Such a study is being undertaken by Abraham Oort at Princeton University. His preliminary results are shown in Figure 6 (see also Oort\(^{34}\)). The results are from an analysis of all standard global radiosonde data (about 500 stations). The global warming of the late 70's and early 80's is clearly accompanied with decreasing specific humidity in the upper troposphere. Although the reduction at 300 mb looks small, it actually amounts to almost 20%. Satellite data supporting this result has recently been analyzed by Chou\(^{35}\) (1993). The implications of this result are truly profound. If it holds up, it unambiguously implies such a strong negative feedback as to hold all changes from increasing CO\(_2\) to a small fraction of a degree (Sun and Lindzen\(^{8}\)). Although error bars are not shown, the trends are large and significant - given the data set. The difficulty with Oort's results is that they have not been corrected for the fact that the instruments used to measure water vapor were changed at many stations during this period (Elliot and Gaffen\(^{36}\), 1991). Incomplete station information makes it difficult to apply such a correction, but it could account for part of the observed decrease in upper level humidity.

It is commonly suggested that society should not depend on negative feedbacks to spare us from a ‘greenhouse catastrophe’. This is a peculiar perversion of science, if the negative feedbacks are a sound consequence of scientific knowledge. Moreover, what is omitted from such suggestions is that current models depend heavily on artificial positive feedbacks to predict high levels of warming. The positive

\(\leftarrow\) There is a societal tendency to give special credence to results obtained with sufficiently large instruments or computers. I would note that such a bias is totally unwarranted.
feedback from clouds has been receiving the closest scrutiny. This is not unreasonable. Cloud cover in models is poorly treated and inaccurately predicted (Kiehl and Williamson\textsuperscript{37}). Yet clouds reflect about 75 watts per square meter. Given that a doubling of CO\textsubscript{2} will change the surface flux by only 2 watts per square meter, it is evident that a small change in cloud cover can strongly effect the response to CO\textsubscript{2}. The situation is complicated by the fact that clouds at high altitudes can also supplement the greenhouse effect. Indeed, the effects of clouds in reflecting light and in enhancing the greenhouse effect are roughly in balance (Ramanathan, et al\textsuperscript{38}). Their actual effect on climate depends both on the response of clouds to warming, and on the possible imbalance of their cooling and heating effects. Stephens, et al\textsuperscript{39} have noted a serious, and unexplained, difficulty with the contribution of layer clouds to greenhouse warming. Such warming involves heating the bottoms of these clouds leading to convective instability within the layer cloud. The resulting instability is incompatible with the observed lifetime of these clouds.

Similarly, feedbacks involving the contribution of snow cover to reflectivity serve, in current models, to amplify warming due to increasing CO\textsubscript{2}. What happens seems reasonable enough; warmer climates presumably are associated with less snow cover and less reflectivity — which, in turn, amplifies the warming. However, snow is associated with winter when incident sunlight is minimal. Moreover, clouds shield the surface from the sun and minimize the response to snow cover. Indeed, there is some evidence that clouds accompany diminishing snow cover to such an extent as to turn this feedback negative (Cess, et al\textsuperscript{40}). If, however, one asks why current models predict large warming will accompany increasing CO\textsubscript{2}, the answer is mostly the water vapor feedback. Current models all predict that warmer climates will be accompanied by increasing humidity at all levels. As already noted, this behavior is an artifact of the models since they have neither the physics nor the numerical accuracy to deal with water vapor. As we have also noted, recent studies of the physics of how deep clouds moisturize the atmosphere strongly suggest that this largest of the positive feedbacks is not only negative, but very large (Sun and Lindzen\textsuperscript{8}).

Clearly there are major reasons to believe that models are exaggerating the response to increasing CO\textsubscript{2}. Perhaps even more significant, the models' predictions for the past century incorrectly describe the pattern of warming and overestimate its magnitude. Figure 7 shows the global average temperature record for the past century or so. The record is irregular and not without problems. However, it does show an average increase in temperature of about 0.45\textdegree C±0.15\textdegree C with most of the increase occurring before 1940, followed by some cooling through the early 70's, and a rapid (but modest) temperature increase in the late 70's. Now, as we have noted,
Figure 7. Combined land air and sea surface temperatures, 1861-1989, relative to 1951-1980. (a) Northern Hemisphere, (b) Southern Hemisphere, (c) Globe. (From Houghton, et al)

we have already seen an increase in 'equivalent' CO₂ of 50%. Thus, on the basis of models which predict a 4°C warming for a doubling of CO₂ we might expect to have seen 2°C already. However, if the delay imposed by the oceans' heat capacity is...
included, the expectation is reduced to about 1°C. This is still twice what has been seen. Moreover, most of what has been seen occurred before the bulk of the minor greenhouse gases were added to the atmosphere. Figure 8 shows what might have

![Graph showing global mean temperature change (°C) from 1860 to 1980.](image)

**Figure 8.** Observed behavior of globally averaged temperatures since 1860, as well as expected behavior from models whose equilibrium response to a doubling of CO$_2$ ($\Delta T_{2x}$) is indicated on the curves. (From Houghton, et al.)

been expected for models with differing equilibrium sensitivities to a doubling of CO$_2$. What we see is that the past record is most consistent with an equilibrium response to a doubling of about 1.3°C — assuming that all the observed warming was due to increasing CO$_2$. However, there is nothing in the record that can be distinguished
from the natural variability of the climate. If one considers the tropics, the situation is even more disturbing. There is ample evidence that the average equatorial sea surface has remained within ±1°C of its present temperature for billions of years (Fairbridge\textsuperscript{15}), yet current models predict average warming of from 2-4°C even at the equator. It should be noted that for much of the Earth's history, the atmosphere had much more CO\textsubscript{2} than is currently anticipated for centuries to come.

**SOME REMARKS ON OCEAN DELAY**

In the introduction to this paper, I made a point of emphasizing the distinction between the equilibrium response to a changing external climate forcing and the time evolution of this equilibrium response. I noted that Hansen, et al\textsuperscript{10} had shown very clearly that the delay imposed by the ocean's heat capacity was not simply a property of the ocean. Rather, it also depended on the climatic feedbacks in the atmosphere. Even the ocean part of the picture is hardly simple; it is not, in general, characterized by a single time scale. However, in order to simplify the discussion, we will focus on a single time scale: namely, the time for a response to reach within (1-e\textsuperscript{-1}) of its equilibrium value. In the absence of any feedbacks, this time scale is on the order of 40 years. This would be the delay time appropriate to a climate system for which the equilibrium response to a doubling of CO\textsubscript{2} would be about 1°C. For a system whose response to a doubling of CO\textsubscript{2} is about 4°C, this delay time is more nearly 150 years, while for a system with an equilibrium response of 0.25°C the delay time would be about 10 years. It is crucial to keep in mind this dependence of the response time on the magnitude of the equilibrium response. In particular, one cannot relate relatively rapid warming events in the data to magnified equilibrium responses. This is true regardless of the nature of the external radiative forcing.

The subtlety of this situation is shown when one considers forcing by aerosols formed from volcanic emissions. Here the forcing is essentially a rapid pulse. The aerosol shield is formed within a few months of the volcanic eruption, and settles out with a characteristic time of about a year (Oliver\textsuperscript{41}). Figure 9 shows the calculated time dependent response to a volcanic eruption for climate systems with various degrees of amplification ranging from 0.2 (strong negative feedback) to 4 (strong positive feedback) using a box-diffusion model for the globally averaged ocean. Surprisingly, the response for the first few years is relatively independent of the system's gain (the differences are comparable to our uncertainty concerning volcanic emissions). Thus, the behavior of the climate over the first few years is hardly a test of the climate model at all!
Figure 9. The response of the globally averaged surface temperature to a volcanic eruption at time=0 for various values of climate gain (g) and a box-diffusion upwelling model of the ocean.

On the other hand, the long time response to an eruption depends a great deal on the system gain. For a system with a 4°C equilibrium response to a doubling of CO₂ about half the maximum cooling resulting from the eruption will persist for over 100 years. Indeed, the long term effects of all volcanic eruptions during this period would tend to accumulate. Thus, the net effect of all the eruptions between Krakatoa (1883) and Sakurashima (1914) would have been a cooling of 0.6-1°C (there was a notable absence of major eruptions between 1914 and 1947). On the other hand, for systems with negative feedback, the volcanic temperature perturbations decay to small values within about a decade, and there is little net accumulation from a sequence of eruptions. Looking at Figure 7, we see no cooling trend during the period of frequent major volcanic eruptions (1883-1914); following this period we see a rapid warming
until 1940 rather than persistently depressed temperatures. If one assumes that the climate system has a gain of 3-4, then the data demand a very large direct (an amplified response involves too long a response time) radiative

**Figure 10.** Superposed epoch analysis of temperature anomalies in the Northern Hemisphere and for 3 latitude zones following the 5 largest explosive eruptions between 1880 and 1988. Horizontal lines indicate the estimated 5% (1 tail) significance level. Temperature anomalies are normalized by standard deviation. The observed cooling corresponds to a global cooling of about 0.4°C. After Bradley⁴².
forcing to compensate for the volcanic cooling. No such forcing has ever been identified. On the other hand, if the system is characterized by negative feedback, no such problem arises; natural variability suffices. This may not prove that the climate system is characterized by negative feedbacks, but it does suggest the problems one encounters in assuming otherwise. As we have already noted, this is hardly the only problem one encounters.

Before leaving the matter of volcanos, it is worth noting one additional feature in Figure 9: namely, for models with very small ‘gains’ (and, hence, very low sensitivities; i.e., less than about 0.25°C for a doubling of CO₂), the temperature minimum associated with a volcano comes about a year after eruption, while for larger gains (associated with larger equilibrium responses to a doubling of CO₂), the minimum occurs two years after eruption. Figure 10 from Bradley⁴² shows a composite of the temperature changes following eruption for the five largest volcanos between 1883 and 1956. Clearly, the maximum cooling occurred within a year of eruption. This strongly suggests such small sensitivity to increasing CO₂ as to leave global temperatures virtually unchanged for even a quadrupling of CO₂.

CONCLUDING REMARKS

In this brief paper, I have barely touched upon numerous and fundamental difficulties with present climate models (such difficulties are discussed by Stone⁴³, 1992). Rather, I have focussed on the specific reasons for current models to predict substantial global warming from increasing CO₂. It is clear that these reasons are essentially spurious. In particular, present predictions of amplified response to CO₂ increases depend crucially on positive feedbacks from upper tropospheric water vapor. Yet the physical processes currently believed to dominate the upper level water vapor budget are largely absent in current models. In addition, there is both observational and theoretical evidence that current predictions are substantially exaggerating the likely warming. None of this constitutes ‘proof’ that significant warming is impossible, but, in the unlikely event that it occurs, it most certainly will not be for the reasons currently put forth. It is sometimes asked, in this connection, how could the climate of the past undergone major changes (ice ages, equable climates, etc.) unless the system were very sensitive. The most recent example of such an approach is Hoffert and Covey¹⁶. These authors assumed that major climate changes of the past (namely, the last major glaciation, and the warm periods of the Cretaceous) were due to differences in CO₂ concentration (observed or inferred) and estimated a sensitivity comparable to what is found in current models. There are at least two problems with such approaches. First, it is assumed that changes in climate must have been due to changes in CO₂; the importance of inhomogeneous forcing, mentioned earlier in this
paper, is ignored. Second, data incompatible with the authors' hypothesis is ignored: namely, the fact that CO₂ levels indicated by the Vostoc core remained high for thousands of years while the earth went into a major glaciation (Barnola, et al44), and the fact that the major Eocene warm period was associated with low CO₂ (Koch, et al45). Indeed, inhomogeneous forcing which alters the dynamic heat flux from low to high latitudes can produce major changes in global climate even in the absence of sensitivity to globally averaged mean radiation (Lindzen and Pan14, Hou46).

Much of the debate on how society should respond to the purported danger of global warming hinges on ones interpretation of and response to 'uncertainty'. In point of fact, there is neither observational nor theoretical basis for expecting substantial warming. However, the possibility has been suggested. Whether the absence of a rigorous disproof of the possibility is a sufficient basis for action is a political question. 'Action' under these circumstances does, however, present certain serious problems. Clearly, there will be no way to establish accountability for the effectiveness of any actions taken. As the IPCC Update (Houghton, et al²) notes, scenarios of markedly increased CO₂ depend primarily on increases in population and living standards in the currently less developed world. They show that proposed OECD emissions caps will, in fact, have a small effect on anticipated global emission levels. Under the circumstances, it will be especially difficult to establish meaningful effectiveness as concerns climate change. Equally clearly, the inclination of society to respond to unfounded suggestions of alleged catastrophe cannot but impede its ability to respond to more concretely identifiable problems. Already, there is substantial momentum for a regulatory approach to this purported problem. It will be of great interest to see whether, in the event that the scientific evidence profoundly diminishes the expected danger, the momentum can be reversed.

ACKNOWLEDGEMENTS

The preparation of this paper was supported by the National Science Foundation under Grant ATM-8520354, and by the National Aeronautics and Space Administration under Grant NAGW-525.

REFERENCES


Page 22


