Senator **Wirth**. Thank you, Dr. Blake.
Dr. Hansen.

STATEMENT OF DR. JAMES E. HANSEN, ATMOSPHERIC SCIENTIST, NEW YORK, NY

Dr. **Hansen**. Senator Wirth and Senator Murkowski, thank you for the opportunity for me to testify. Before I begin, I would like to state that although I direct the NASA/Goddard Institute for Space Studies, I am appearing here as a private citizen on the basis of my scientific credentials.

The views that I present are not meant to represent in any way agency or administration policy. My scientific credentials include more than 10 years experience in terrestrial climate studies and more than 10 years experience in the exploration and study of other planetary atmospheres.

I will summarize the result of numerical simulations of the greenhouse effect, carried out with colleagues at the Goddard Institute. Previous climate modeling studies at other laboratories and at our own examined the case of doubled carbon dioxide, which is relevant to perhaps the middle of the next century based on expected use of fossil fuels.

The unique aspect of our current studies is that we let CO_2 and other trace gases increase year by year as they have been observed in the past 30 years, and as projected in the next 30 years. This allows us to predict how climate will change in the near term, and to examine the question of when the greenhouse effect will be apparent to the man in the street.

[Viewgraph.]

We began our climate simulation in 1958 when CO_2 began to be measured accurately, as shown on the first viewgraph. Measurements of other trace gases such as methane, chlorofluorocarbons and nitrous oxide began more recently, but their trends can be estimated with reasonable accuracy back to 1958.

For the future, it is difficult to predict reliably how trace gases will continue to change. In fact, it would be useful to know the climatic consequences of alternative scenarios. So we have considered three scenarios for future trace gas growth, shown on the next viewgraph.

Scenario A assumes the CO_2 emissions will grow 1.5 percent per year and that CFC emissions will grow 3 percent per year. Scenario B assumes constant future emissions. If populations increase, Scenario B requires emissions per capita to decrease.

Scenario C has drastic cuts in emissions by the year 2000, with CFC emissions eliminated entirely and other trace gas emissions reduced to a level where they just balance their sinks.

These scenarios are designed specifically to cover a very broad range of cases. If I were forced to choose one of these as most plausible, I would say Scenario B. My guess is that the world is now probably following a course that will take it somewhere between A and B.

We have used these three scenarios in our global climate model, which simulates the global distribution of temperatures, winds, and other climate parameters. Running our model from 1958 to the year 2030, the results for the global mean temperature are as shown in the next viewgraph. The model yields warming by a few tenths of a degree between 1958 and today. In fact, the real world shown by the black curve, has warmed by something of that order.

This warming is not large enough relative to the natural variability of climate, for us to claim that it represents confirmation of the model. But we may not have long to wait if warming of 0.04 of a degree centigrade which is three times the standard deviation of the natural variability of the global temperature, if that is maintained for several years that will represent strong evidence that the greenhouse effect is on this track.

If the world follows trace gas Scenario A or B or something in between, the model says that within 20 years global mean temperature will rise above the levels of the last two interglacial periods and the earth will be warmer than it has been in the past few hundred thousand years.

The man in the street is not too concerned about global mean, annual mean temperature, so let us look at maps of the predicted temperature change for a particular month.

The next viewgraph shows the computed temperature anomalies for July for the intermediate Scenario B. This shows July, 1986 in the upper left, going to July of 1987, 1990 and then on the right, 2000, 2015 and 2029. The yellows and reds are the areas that are significantly warmer than the 1950's climatology. Blues are areas that are colder than normal.

The map, for any given month, represents natural fluctuations or noise of the climate system as well as a long term trend due to the greenhouse effect.

The natural fluctuations are an unpredictable sloshing around of a nonlinear fluid dynamical system. So, these maps should not be taken as predictions of the precise patterns for a particular year.

One conclusion that I want to draw from these maps is that at the present time in the 1980's in a given month, there are almost as many areas colder than normal as areas warmer than normal. This is because the greenhouse warming is smaller than the natural fluctuation of regional climate.

You can see that by 13 years from now, the year 2000, the probability of being warmer than normal is much greater than being cooler than normal. In a few decades from now, it is warm almost everywhere.

So, how important are temperature anomalies of this magnitude? One indication is provided by recent experience in the real world. The next viewgraph shows observational data for July 1986 on the top and July, 1987 on the bottom.

You probably remember that in July of 1986 there was a heat wave in the Southeast United States, and in July of 1987 it was warm on the east coast. The same color scale is used here as for the model results, so you can use the last two July's in the real world to gage the yellow and red colors in the preceding maps.

This makes it obvious that the model predictions for the future shown on the earlier graph represent a major increase in the frequency and severity of July heat waves.

In the letter requesting my testimony, you asked me specifically to address the question of how the greenhouse effect may modify the temperatures in the Nation's city. The next viewgraph shows estimates of the number of days per year in which the temperature exceeds a given threshold.

For example for Washington, DC, the number of days in which the temperature exceeds 100 degrees fahrenheit has been one day per year on the average in the period 1950 to 1983. In the doubled CO_2 climate, which will be relevant to the middle of the next century if the world follows trace gas Scenario A, there are about 12 days per year above 100 degrees fahrenheit.

The number of days per year with temperature exceeding 90 degrees fahrenheit increases from about 35 to 85, and the number of nights in which the minimum does not drop below 80 degrees fahrenheit increases from less than one per year to about 20 per year in our climate model.

Obviously, if the greenhouse effect develops to this extent, it will have major impacts on people. The doubled CO_2 level of climate change is not expected until, perhaps the middle of the next century. It is difficult to predict when, because it depends upon which emission scenario the world follows.

Predictions for the more immediate future are shown on the next viewgraph. This shows the number of days with temperatures exceeding 90 degrees fahrenheit decade by decade. Climatology is the 1950's through the 1970's. The results for Scenario A, which we described as business as usual are on the left.

Scenario C on the right, has drastic and probably implausible emission cuts. The conclusion that I draw from this graph is that climate impacts depend greatly on the emission scenario which the world follows.

The climate impacts in Scenario A become dramatic by the 2030's, but in Scenario C, the mean effect remains smaller than the year to year natural variability.

Finally, I would like to comment on an obvious question: How good are these climate predictions? The climate models we employ and our understanding of the greenhouse effect have been extensively tested by simulations of a range of climates which existed at past times on the earth and on other planets.

So, we know the capabilities and limitations of the global models reasonably well. There is, in fact, a substantial range of uncertainty in the predicted temperature change. For example, we can only say that the global climate sensitivity, the doubled CO_2, is somewhere in the range from 2 degrees centigrade to 5 degrees centigrade.

The model used in our studies has a sensitivity of 4 degrees centigrade, which is in the middle of the range obtained from other global climate models.

The geographical patterns of greenhouse climate effects are uncertain, especially changes in precipitation, as Dr. Manabe will discuss. However, the uncertainties in the nature and patterns of climate effects cannot be used as a basis for claiming that there may not be large climate changes.

The scientific evidence for the greenhouse effect is overwhelming. The greenhouse effect is real, it is coming soon, and it will have major effects on all peoples. As greenhouse effects become apparent, people are going to ask practical questions and want quantitative answers. Before we can provide climate projections with the specificity and the precision that everyone would like, we first must have major improvements in our observations and understanding of the climate system.

In my submitted testimony, I have listed observations which I believe are most crucial. I believe it is very important that observational systems be in place by the 1990's as greenhouse effects become significant. That is necessary if we are to be able to provide decision-makers and improved information as the greenhouse effect grows, and its importance to society.

Thank you for this opportunity to express my opinion.

[The prepared statement of Dr. Hansen follows:]

PREDICTION OF NEAR-TERM CLIMATE EVOLUTION:
WHAT CAN WE TELL DECISION-MAKERS NOW?

STATEMENT OF:

James E. Hansen
33 North Pleasant Avenue
Ridgewood, NJ 07450

PRESENTED TO:

United States Senate

Committee on Energy and Natural Resources

November 9, 1987

Mr. Chairman, thank you for inviting me to testify before the Senate Committee on Energy and Natural Resources. My testimony today is in response to your letter of November 2, 1987, which requested my "views on the likely pace and regional implications of the greenhouse effect and global climate change, with specific reference to temperature changes in the nation's cities." I am appearing today as an expert on global climate and global change, based on my experience of more than 10 years in terrestrial climate studies and more than 10 years in the exploration and study of other planetary atmospheres. Although I direct the NASA Goddard Institute for Space Studies, I am appearing on the basis of my scientific credentials; the views that I present are not meant to represent in any way agency or administration policy.

My testimony will be in part a review of existing scientific knowledge about the greenhouse effect and in part a description of current climate model research at the Goddard Institute for Space Studies in which my colleagues (I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, P. Stone) and I have simulated the unfolding of greenhouse climate effects during the next 10-30 years. Previous simulations of greenhouse effects have been confined to the case of doubled carbon dioxide, relevent to the middle of the 21st century; thus I must rely on the current results from the GISS model for discussion of climate trends during the near-term. I will confine my discussion to temperature changes. Dr. Manabe will testify about impacts of the greenhouse effect on precipitation and soil moisture.

I hope that in my presentation I can find an appropriate middle ground between the preference of scientists to stress all caveats in detail, and the desire of non-technical parties for an understandable practical statement of the status of scientific understanding.

1. Are Major Greenhouse Climate Changes a Certainty?

Our understanding of the greenhouse effect is based on a broad range of evidence, both theoretical and empirical. Global climate models or general circulation models (GCMs), which are mathematical representations of the atmosphere and ocean used to simulate weather and climate change on large scale computers, suggest that a doubling of atmospheric carbon dioxide will cause a global mean warming of somewhere between 2.5° and 5.5°C. Results from all the GCMs are thus consistent within about a factor of two.

Empirical evidence about climate sensitivity is more important, in my opinion, and it is consistent with the climate model results. Principal empirical evidence is summarized in Fig. 1. The inner planets Venus, Earth and Mars have a broad range of greenhouse gas abundances; Venus has a very thick CO_2 atmosphere, the earth's atmosphere is of intermediate thickness, and Mars has a thin CO_2 atmosphere. Each of these planets is warmer than it would be without an atmosphere, given their distances from the sun. Venus has a greenhouse effect of several hundred degrees, the earth is 33°C warmer than it would be without its greenhouse gases, and Mars has a greenhouse effect of only a few degrees. The observed temperatures are consistent with the theoretical expectations for the observed atmospheric composition on each planet.

Remarkable confirmation of our understanding of climate sensitivity has been developed in the 1980's from paleoclimate records, the principal advance being accurate determination of fluctuations in atmospheric CO_2 during the past 100,000 years. Although scientists continue to debate why CO_2 changed, a great deal of information is available on how CO_2 and other climate parameters (such as land ice, sea ice cover, vegetation distribution, and earth orbital parameters) differed between ice ages and interglacial periods. This allows quantification of the contribution of different processes to a well documented large global climate change. The important result is empirical evidence for an equilibrium climate sensitivity of about 2.5-5°C for doubled CO_2, consistent with the sensitivity of global climate models.

Additional empirical evidence is provided by the observed global warming of about 0.6°C in the past century. This is consistent with the expected warming due to known increases of atmospheric CO_2 and trace gases in that period. This empirical evidence does not provide as precise a measure of climate sensitivity as we might hope, because part of the warming due to increased greenhouse gases is delayed due to the thermal inertia of the oceans; the delay is greater if climate sensitivity is greater, so the short-term temperature rise is not so different between cases of low and high climate sensitivity. This ambiguity could be removed if we measured accurately the rate of heat storage in the ocean. At this time we can only say that the observed warming in the past century is consistent with any climate sensitivity in the range 2-5°C for doubled CO_2.

<u>Conclusion</u>: in view of the facts that (1) even conservative projections of CO_2 and trace gas growth indicate an equivalent doubling of CO_2 by the second half of next century, and (2) the warmest time in the past 100,000 years was only about 1°C warmer than today (cf. Fig. 2), we can confidently state that major greenhouse climate changes are a certainty. However, as shown by results below for different trace gas scenarios, the impacts are much less in scenarios with reduced trace gas growth rates.

2. Can we predict greenhouse climate changes that will occur in the near-term, say in the next 10-30 years?

Prediction of near-term climate trends, as opposed to equilibrium doubled CO_2 climate changes, introduces several major complications. First, we must give up the luxury of using an arbitrarily fixed CO_2 change, and instead consider how CO_2 and trace gas abundances might evolve in the real world. Second, instead of solving for an equilibrium response relevant to some poorly specified far-future date, we must tackle the time-dependent response of the climate system; that means we must account for the ocean's role in climate change, since the ocean is the principal source of thermal inertia in the climate system. Third, because near-term greenhouse climate effects are small compared to those for doubled CO2, we must be concerned about other climate forcings which may be comparable to greenhouse gases, and we must compare predicted climate changes to natural variability of the system.

<u>Trace gas scenarios</u>. CO_2 and other trace gas abundances are reasonably well known for the period since 1958, when CO_2 began to be monitored accurately, as illustrated in Fig. 3. Although it is very difficult to predict future trends, our objective is to consider a broad range of scenarios to help evaluate the implications of different alternatives. The three scenarios we employ (Fig. 4) are:

Scenario A - continued growth of emissions at rates which are compounded annually, and thus are exponential; e.g., CO_2 emissions increase 1½%/year and CFC emissions increase 3%/year.

Scenario B - fixed annual growth of greenhouse forcing; if population grows, this scenario implies a reduction in per capita emissions.

Scenario C - greenhouse forcing ceases to increase after year 2000; CFC emissions are terminated by 2000 and other trace gas emissions just balance their sinks; this would require drastic cuts in fossil fuel use, perhaps half of the current use.

In view of resource constraints and environmental concerns, Scenario A must eventually yield unrealistically large greenhouse forcing. Scenario C, on the other hand, represents a more drastic curbing of emissions than usually has been contemplated. Scenario B is probably the most plausible of the three scenarios.

Transient ocean response. The time dependent response of the climate system to changes of climate forcing depends principally upon the ocean. Unfortunately, capabilities for modeling the global ocean are much more primitive than capabilities for modeling the atmosphere. As a result, for the climate simulations which we present here we make a gross simplifying assumption about ocean heat transports: we assume (1) that for the next few decades the pattern of horizontal heat transport by ocean currents will remain the same as it is today, and (2) heat perturbations penetrate the deep ocean at a rate based on observed penetration of inert tracers (such as tritium sprinkled on the ocean in nuclear testing).

Although these assumptions are plausible for small climate perturbations, it must be recognized that we are thereby forcing the ocean to be relatively surprise-free. In the real-world, climate changes at the ocean surface may induce changes in ocean heat transports, thus leading to other, perhaps larger, climate changes. Broecker, for example, has stressed the possibility of changes in Gulf Stream and related ocean transports. Especially because of these assumptions about the ocean, it is unlikely that we can predict regional climate surprises; this is somewhat analogous to the difficulty that atmospheric chemistry models have in predicting or simulating post facto the Antarctic ozone hole.

Other climate forcings. At the present time the climate forcing due to increasing greenhouse gases is not large enough to completely dominate other global climate forcings such as changes of atmospheric aerosols or changes of solar irradiance (Fig. 5). For example, the solar irradiance was observed to decrease by ~ 0.09% between 1979 and 1985, which represents a somewhat larger forcing (of the opposite sign) than the forcing due to the atmospheric CO_2 increase in the same period. An even larger global climate forcing occurred in the period 1982-84 due to stratospheric aerosols generated by the volcano El Chichon (Fig. 5, lower panel), which would tend to cause a global cooling for at least that period.

Climate forcings such as changes in solar irradiance and stratospheric aerosols increase and decrease with time, and thus eventually are overwhelmed by monotonically increasing greenhouse gases. But on the time scale of a decade or so, the climate effects of these other forcings may be noticeable and impact our ability to detect the greenhouse effect. In our climate simulations we include the climate forcing due to stratospheric aerosols; we employ available measurements of aerosol opacity for the period 1958 to the present and we examine the impact of alternative assumptions for the level of future volcanic activity. We do not include variations of solar irradiance, because measurements are only available for the past several years. It is important that these climate forcings continue to be monitored to allow interpretation of current and future climate trends.

Conclusion: We can simulate greenhouse climate effects for assumed future trace gas scenarios, but, in addition to being aware of the uncertainty in climate sensitivity, which was discussed above, we must recognize the implications of simplifying assumptions about the ocean. Moreover, the impact of other climate forcings can be comparable to the greenhouse effect in the near-term. Finally, predicted greenhouse climate effects must be compared with the magnitude of unforced climate fluctuations.

3. Simulations of Near-Term Climate Change.

We present here sample results from the transient climate change simulations with the GISS GCM. This GCM, schematically illustrated in Fig. 6, has been documented elsewhere (Mon. Wea. Rev., 111, 609-662, 1983; AGU Geophys. Mono. 29, 130-163, 1984). The principal characteristics affecting the simulations reported here are:

Global sensitivity: the model has a sensitivity of about 4°C for doubled CO_2; ocean transports: horizontal transport by ocean currents is specified, based on estimates for today's ocean; uptake of heat perturbations by the deep ocean is mimicked as a diffusive process dependent on local stability of the water column, calibrated by measurements of transient tracers; trace gas growth: scenarios employed are illustrated in Fig. 4; stratospheric aerosols: observed trends are used for the period 1958-1985, which included large volcanic injections by Mt. Agung in 1963 and El Chichon in 1982; scenario A assumes that near-term future volcanic aerosols will be negligible, as was the case in 1915-1960; scenarios B and C assume a volcanically active future, as in the period 1958-1985, by inserting large volcanoes in 1995, 2015, 2025; other climate forcings: no changes of solar irradiance or other climate forcings are included.

The computed global mean temperature trends for scenarios A, B and C are illustrated and compared with observations in Fig. 7. Interpretation of Fig. 7 requires quantification of the magnitude of natural variability, in both the model and observations, and the uncertainty in the measurements. The standard deviation of the model's global mean temperature is about 0.1°C. The standard deviation about the 100 year mean for the observed surface air temperature trend of the past century (which has a strong trend) is 0.20°C; it is 0.12°C after detrending (Science, 214, 957-966, 1981). It is not surprising that the variability of the observed global temperature exceeds the variability in the GCM control run, since the latter contains no variable climate forcings such as changes of atmospheric composition or solar irradiance. Finally, we note that the one-sigma error in the observations due to incomplete coverage of stations is about 0.05°C for the period 1958-1985 (Hansen and Lebedeff, J. Geophys. Res., in press), which does not contribute appreciably to the 0.12°C variability (standard deviation) of the observed global temperature. We conclude that a warming of about 0.4°C is required to be significant at the 3σ level (99% confidence level).

There is no clearly significant warming trend in either the model or observations for the period 1958-1985. During the single year 1981 the observed temperature nearly reached the 0.4°C level of warming, but by 1985 the observed temperature was no greater than in 1958.

The model predicts, however, that by the late 1990's the global temperature will reach and maintain a 3σ level of global warming, which is clearly significant. Although this conclusion depends upon certain assumptions, such as the climate sensitivity of the model and the absence of large volcanic eruptions in the next few years, it is robust for a very broad range of assumptions about CO_2 and trace gas trends, as illustrated in Fig. 7.

Another conclusion is that global warming to the level attained at the peak of the current interglacial and the previous interglacial is inevitable; even with the drastic, and probably unrealistic, reductions of greenhouse forcings in scenario C, a warming of 0.5°C is attained within the next 15 years. The eventual warming in this scenario would exceed 1°C, based on the forcing illustrated in Fig. 2 and the climate sensitivity of our GCM. The 1°C level of warming is exceeded during the next few decades in both scenarios A and B; in scenario A that level of warming is reached in less than 20 years and in scenario B it is reached within the next 25 years.

The geographical distribution of the predicted surface air temperature change for the intermediate scenario B is illustrated in the left column of Fig. 8 for the 1980's, the 1990's and 2010's. The right column is the ratio of this decadal temperature change to the interannual variability (standard deviation) of the local temperature in the 100 year control run of the GCM. Since the interannual variability of surface air temperature in the model is reasonably similar to the variability in the real world, this ratio provides a practical measure of when the predicted mean greenhouse warming is locally significant.

Averaged over the full decade of the 1980's, the model indicates a tendency toward warming, but in most regions the decadal-mean warming is less than the interannual variability of the annual mean. In the 1990's the decadal-mean warming is comparable to the interannual variability for many regions, and by the 2010's essentially the entire globe has very substantial warming, as much as several times the interannual variability of the annual mean.

The man-in-the-street is more likely to notice whether the monthly mean climate is hotter or colder than normal, rather than changes of decadal mean temperature. Thus in Fig. 9 we illustrate maps of computed temperature anomalies for a particular month (July) in several different years. These maps illustrate that when the temperature is averaged over a period as short as one month, there are in the 1980's about as many areas colder than normal as warmer than normal. A noticeable trend toward warming occurs within 10-15 years, illustrated by model results for 2000, but at that time there are still many areas with monthly mean-temperatures colder than normal. However, after a few decades, the great majority of regions are significantly warmer than normal in any given month.

We stress that temperature maps for any given month and year represent natural fluctuations (noise) of the climate system as well as some long-term trend due to greenhouse forcing of the climate system. The natural fluctuations are an unpredictable "sloshing around" of a nonlinear fluid dynamical system.

Thus the maps for a specific month and year should not be taken as a prediction of detailed temperature anomaly patterns for that particular year.

It is fair, however, to examine the maps for consistent patterns and trends which can be related to physical mechanisms. For example, the warming is generally greater over continental areas than over the ocean, and greater at high latitudes than at low latitudes. The first result is expected because the oceans respond more slowly than the continents to the greenhouse heating, as a result of the ocean's large heat capacity. The surface warming in the model is greater at high latitudes than at low latitudes, because of the greater stability of the atmosphere at high latitudes and the positive sea ice/albedo feedback there.

We also note a tendency for the computed warming in the 1980's and the 1990's to be relatively greater than average over the U.S. southeast and less over the western United States and parts of Europe. Changes in sea level pressure patterns associated with ocean areas which warmed relatively little may provide a mechanism for such a tendency. However, very different patterns occur in some years. Moreover, it should be remembered that ocean heat transports were fixed in our model; changes in ocean transports could greatly modify the geographical patterns of temperature change.

Conclusion: The climate model results indicate that greenhouse effects on near-term global temperature trends should be apparent within the next several years. The computed greenhouse warming remains smaller than the natural variability of regional monthly mean temperature for the next decade or two, but a tendency for more warm areas than cool areas becomes apparent in the model by the 1990's.

4. Observed Climate Trends.

Estimates of surface air temperature trends are based on measurements recorded at about 2000 meteorological stations which are very unevenly distributed over the globe. The uncertainties in the inferred global temperature trend are investigated quantitatively in attachment A (cf. p. 11), which will be published in the Journal of Geophysical research in November 1987. The graphs presented here are derived from that publication, but we emphasize that our results are consistent with those of other researchers (such as Wigley, Jones and others at the University of East Anglia, and J. Angell of Air Resources Laboratory, NOAA) for the common periods of analysis.

Observed surface air temperature anomalies for the first seven years of the 1980's are illustrated in Fig. 10a. There is evidence of warming in the observations, and the locations of greatest warming, in Asia and at high latitudes, are not inconsistent with the model simulation (Fig. 8). As indicated by Fig. 8, a much more conclusive comparison of the model and observations will be possible by the 1990's.

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The temperature data available for 1987 is shown in Fig. 10b. For the available months, 1987 is a remarkably warm year, indeed the warmest in the history of recording instruments. North America is particularly warm, with some areas more than 3°C above 1951-1980 climatology, while Europe is relatively cool. Low latitudes are very warm, which undoubtedly is a result of the El Nino which has been taking place during 1987. An El Nino involves the spreading of warm surface waters over certain low latitude ocean regions which normally have upwelling cold deep water; the phenomenon occurs aperiodically at intervals of about 2-5 years and tends to result in warming of the entire tropical troposphere.

As stressed in Section 3, monthly mean temperature anomalies are of great practical importance. Observations for July 1986 and July 1987 are shown in Fig. 11. Fig. 11 illustrates, for example, that the Southeast U.S. was warm in July 1986 and the entire eastern seaboard of the U.S. was warm in July 1987. In both of these years there are about as many midlatitude regions which are colder than normal as there are regions warmer than normal.

One reason we have illustrated observations for specific months is that it allows a calibration of the magnitude of regional anomalies which we have recently experienced, such as the warm Julys in the Southeast and on the eastern seaboard of the United States. Since the same color scale was used for the model simulations in Fig. 9, it is apparent that the model predictions for future decades represent a substantial increase in the frequency of such warm events as well as a substantial increase in the severity of the warmest events.

The global temperature trend for the past century, including the partial result for 1987, is shown in Fig. 12. The earth's temperature increased by 0.5°C between the 1880's and 1960, decreased by 0.2°C between 1940 and 1965, and has increased at a rapid rate since 1965. An estimate of the rate of the current warming trend depends considerably on whether the temperature in the next few years remains near the 1987 level. Indeed, at least a temporary decrease from the 1987 level should be anticipated, in view of the probable contribution of the current El Nino to the 1987 global temperature.

Conclusion: Observations indicate a strong warming trend from the mid 1960's to the present. The global temperature in the 1980's is at the highest level in the history of recorded measurements, despite recent trende of solar irradiance and stratospheric aerosols which tend to cool the earth's surface. We conclude that there is strong evidence for an underlying warming trend, but a definitive association with the greenhouse effect requires further data and studies as described in the final section below.

5. Climate Impacts: Will the Temperature Changes Be Significant to the Man-in-the-Street?

The global warming predicted to occur in the next 20 years will make the earth warmer than it has been in the past 100,000 years. It can be assumed that there will be major practical impacts of such a warming, but little research has been done to define such impacts. Indeed, warming by a few degrees may seem to be a small effect to the man-in-the-street since weather fluctuations are larger than that.

We have estimated how greenhouse warming will alter the number of days in which temperatures exceed a given threshold as a means to illustrate that warming by a few degrees (centigrade) is a large climate change. Although global climate models are not designed for local studies, we can obtain this estimate by compiling climatological data for a given city from a long series of daily observations (including maximum and minimum temperatures for each day) and adding to this record the mean (monthly) increase in daily maximum temperature and in daily minimum temperature as predicted by the climate model for the gridboxes nearest that city. This procedure tends to minimize the effects of any errors in the model's control run climatology. Although the procedure neglects changes in the higher moments of the temperature distribution, examination of our model results indicates that such changes are small.

We first carried out this procedure for the warming predicted by climate models as an equilibrium response to doubled atmospheric CO_2. This is a large climate change, some 4-5°C in the United States, which would be applicable to the middle of next century, if the trace gas growth rate of Scenario A is approximately correct and if the climate sensitivity of current GCMs is approximately correct.

The results of this exercise for doubled CO_2 are shown in Fig. 12 for several cities in the United States. The number of days per year in which the maximum daily temperature exceeds 100°F (38°C) increases from about one to 12 in Washington and from three to 20 in Omaha. The number of days with maximum temperature exceeding 90°F (32°C) increases from about 35 days to 85 days in both cities. The number of days per year in which the nighttime temperature does not fall below 80°F (27°C) increases from less than one day in both cities to about 10 days in Omaha and about 20 days in Washington, D.C. Analogous results for six other U.S. cities are included in Figure 12.

We reiterate here the principal reasons why these estimates may differ from the real world response. First, the estimates are based on a model with a sensitivity of 4°C for doubled CO_2; the real world sensitivity is uncertain within the range from about 2°C to 5°C. Second, the model assumes that the ocean will continue to transport heat essentially as it does today; if North Atlantic deep water formation and the Gulf Stream should be substantially modified, for example, that could change the results for a location such as Washington, D.C. And third, there are many small-scale processes that are not resolved by the model, which could cause local responses to vary.

We make similar estimates for the number of days with temperatures exceeding 90°F for the smaller climate changes which are expected during the next few decades for our extreme trace gas scenarios A and C (Fig. 14). In scenario A, profound changes in the climate would be obvious to the man-in-the-street within the first few decades of the twenty-first century. On the other hand, in scenario C the changes in decadal mean values remain smaller than the year-to-year fluctuations in the number of days with extreme temperatures. This does not imply that the climate change in scenario C is negligible, but scenario C obviously would have much smaller practical impacts than would scenario A.

Conclusion: Although there has been little quantitative research on climate impacts of greenhouse warming, it is apparent that the temperature changes predicted to result from trace gas scenarios A and B would dramatically alter the climate perceived by the man-in-the-street.

6. Climate Response Time: Implications for Emissions Policies

One aspect of the greenhouse climate problem which is particularly relevant to policy considerations is the response time of the climate system. Principally because of the great heat capacity of the oceans, the earth does not immediately respond to a change in climate forcing, but rather tends to adjust slowly over a period of years. Unfortunately, we do not yet have an accurate assessment of what the climate response time is.

The climate response time is in fact a function of climate sensitivity, as described in attachment B (cf. p. 11). If climate sensitivity is only 1.5-2°C for doubled CO_2, the response time may be only of the order of 10 years. But if climate sensitivity is 2.5-5°C, as current GCMs suggest, the response time is in the range from a few decades to a century.

The implication is that a large part of the warming attributable to trace gases man has added to the atmosphere probably has not yet appeared. In addition to the warming which has occurred over the past century, we are committed to additional warming, even if increases of trace gases should be terminated immediately.

Determination of the magnitude of this unrealized warming would be greatly aided by research directed at improving our understanding of climate sensitivity. The single measurable quantity which would be most helpful in this regard is the rate at which heat is being stored in the ocean. Higher climate sensitivities (and hence greater values for the amount of unrealized warming already 'in the bank') have associated with them greater rates of heat storage in the ocean. Accurate monitoring of ocean temperature along a number of ocean transects is required for this purpose. Other key measurement needs are mentioned in the next section.

Conclusion. The finite response time of the climate system implies that there is unrealized greenhouse warming already 'in the bank' or 'in the pipeline'. This yet to be realized warming calls into question a policy of "wait and see" regarding the issue of how to deal with increasing atmospheric carbon dioxide and other trace gases.

7. What is Needed to Improve Understanding of the Greenhouse Effect and Climate Predictive Capabilities?

Scientific evidence confirming the essence of the greenhouse theory is overwhelming. The greenhouse effect is real, it is coming soon, and it will have major effects on all peoples. The greenhouse issue has not received the attention it deserves because the climate trends have not yet risen clearly above the level of natural climate variability. However, based on our model results, greenhouse effects should begin to be apparent within the next decade.

As greenhouse climate change begins to appear, people will ask practical questions and want quantitative answers. We are now totally unprepared to provide information of the specificity that will be required. Vast improvements are needed in our understanding of the climate system and our ability to numerically simulate climate change. Key areas requiring better knowledge include the ocean circulation and heat storage, ice sheet dynamics, ground moisture and vegetation distributions, and climate feedback processes involving cloud properties, sea ice cover, the atmospheric water vapor distribution, and effects of climate change on atmospheric trace gas abundances. These research tasks will require major long-term efforts

The greatest need, in my opinion, is for global observations of the climate system over a period of at least a decade. It is important that observational data systems be in place by the 1990's, as greenhouse effects become significant. Observations are needed to document and quantify climate trends, to allow testing and calibration of global climate models, and to permit analysis of many small-scale climate processes which must be parameterized in the global models. The data needs will require both monitoring from satellites and in situ studies of climate processes. A comprehensive discussion of required observations has been prepared by the Earth System Sciences Committee (appointed by the NASA advisory council) and is presently in press [Earth System Science: A Closer View].

Conclusion: As greenhouse climate effects inevitably grow, so will the needs for quantitative evaluation of observed climate change and reliable prediction of the consequences of alternative trace gas emission scenarios. This will require long-term global observations of the climate system accompanied by a vigorous research program.

Acknowledgement. The graphics for this testimony were produced on short notice by P. Palmer, J. Jonas and J. Mendoza.

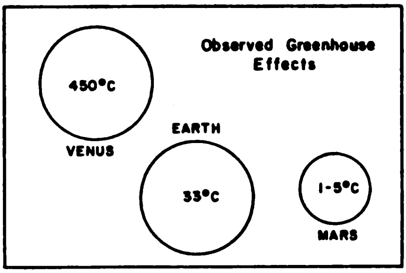
Attachments*

A. Global Trends of Measured Surface Air Temperature, J. Hansen and S. Lebedeff, Journal of Geophysical Research, November, 1987 (in press).

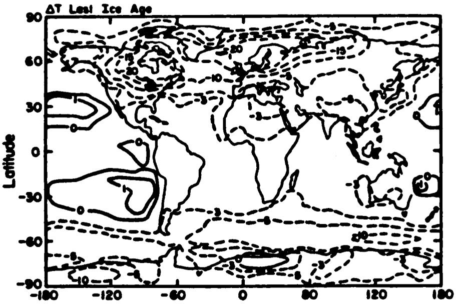
B. Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing, J. Hansen, G. Russell, A. Lacis, I. Fung, D. Rind and P. Stone, Science, 229, 857-859, 1985.

* Because of its length (28pp.) attachment A is included only with the primary copy of this testimony; copies of it are available from NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025

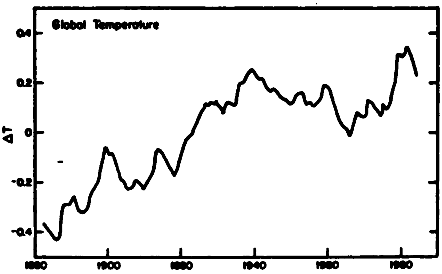
EMPIRICAL BASIS OF UNDERSTANDING



OTHER PLANETS:
Venus (400°C), Earth (15°C) and Mars (-50°C) have a broad range of temperatures consistent with greenhouse gas abundances



PALEOCLIMATE RECORDS:
Glacial to interglacial climate changes were accompanied by large changes in atmospheric CO_2, which appear to have been the principal mechanism of climate change



RECENT CLIMATE TRENDS:
Global warming of 0.6°C (1°F) in the past century is consistent with the increase of atmospheric CO_2 and trace gases in that period

Fig. 1. Examples of empirical data which provide quantitiative estimates of climate sensitivity.

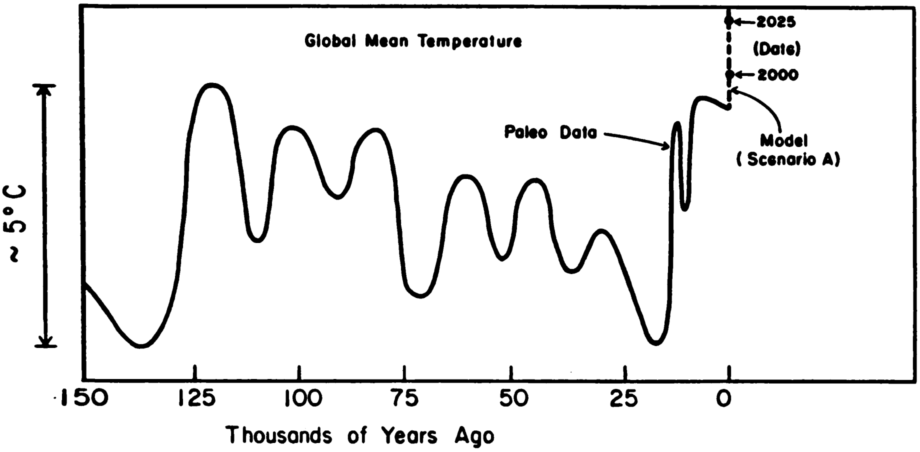


Fig 2. Smoothed global mean temperature trend during the past 150,000 years, and the simulated future temperature trend for trace gas emission scenario A.

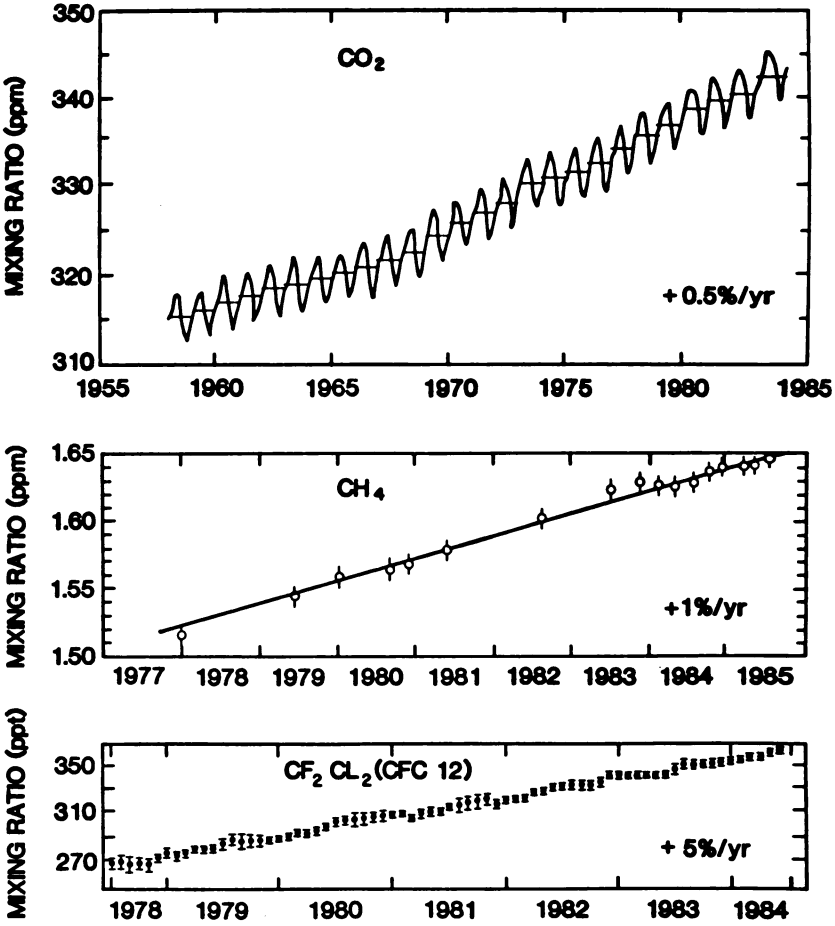


Fig. 3. Recent trends in the atmospheric abundance of three of the principal greenhouse gases in the earth's atmosphere.

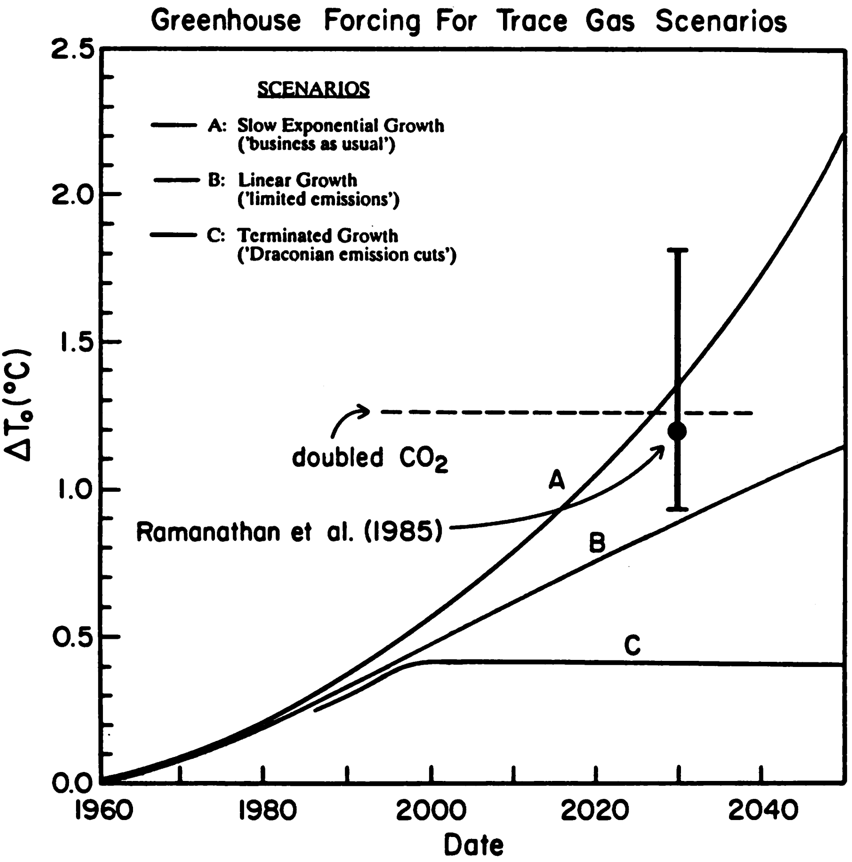


Fig. 4. Three trace gas scenarios used for simulations of future climate with the GISS GCM, as described in the text. ΔT_0 is the "greenhouse forcing", specifically the equilibrium mean global warming that would occur if there were no climate feedbacks. The doubled CO_2 level of forcing, $\Delta T_0 \approx 1.25°C$, occurs when the CO_2 and trace gases added after 1958 provide a forcing equivalent to doubling CO_2 from 315 ppm to 630 ppm. The CO_2 + trace gas forcing estimated by Ramanathan et al. (J. Geophys. Res., 90, 5547-5566, 1985) for 2030 is also illustrated.

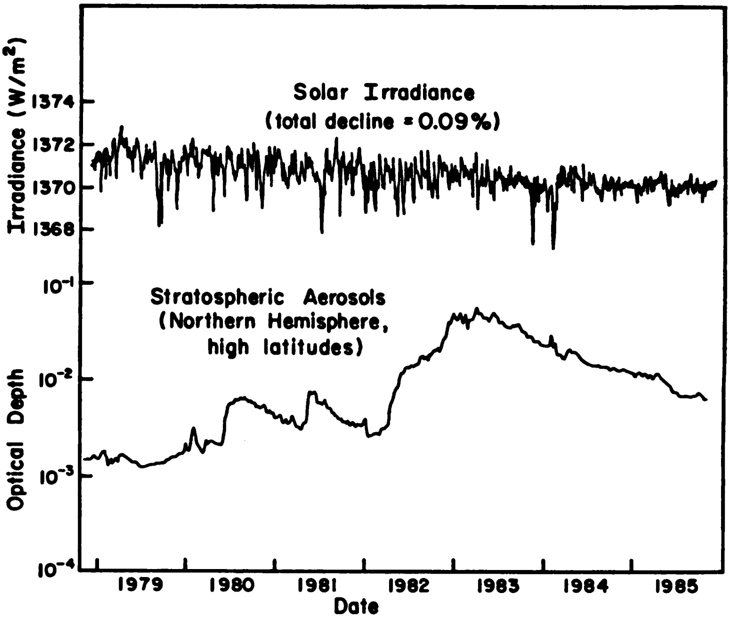
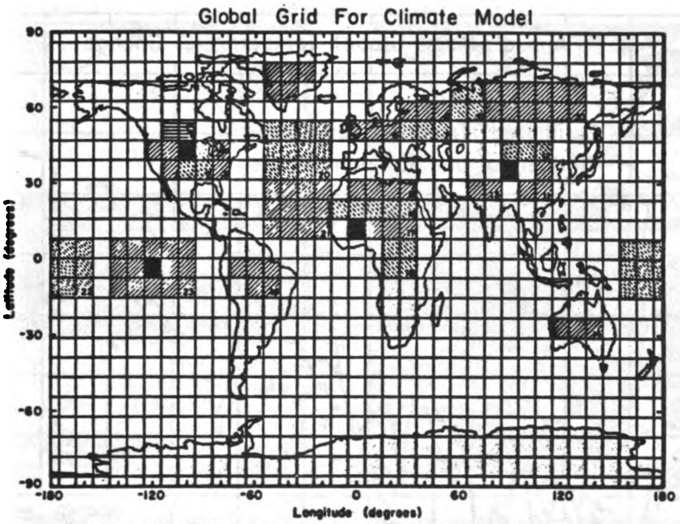


Fig. 5. Solar irradiance and optical depth of stratospheric aerosols, both as observed from the NASA Nimbus 7 satellite.

Global Grid For Climate Model



Fundamental Equations

Conservation of momentum: (Newton's second law of motion)

$$\frac{d\mathbf{V}}{dt} = -2\boldsymbol{\Omega} \times \mathbf{V} - \rho^{-1}\nabla p + \mathbf{g} + \mathbf{F} \tag{T1}$$

Conservation of mass: (continuity equation)

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{V} + C - D \tag{T2}$$

Conservation of energy: (first law of thermodynamics)

$$\frac{dI}{dt} = -p\frac{d\rho^{-1}}{dt} + Q \tag{T3}$$

Ideal gas law: (approximate equation of state)

$$p = \rho RT \tag{T4}$$

Notation

$\mathbf{V}$	velocity relative to rotating earth
t	time
$\frac{d}{dt}$	total time derivative $\left[= \frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right]$
$\boldsymbol{\Omega}$	planet's angular rotation vector
ρ	atmospheric density
$\mathbf{g}$	apparent gravity [=true gravity $- \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r})$]
$\mathbf{r}$	position relative to planet's center
$\mathbf{F}$	force per unit mass
C	rate of creation of (gaseous) atmosphere
D	rate of destruction of atmosphere
I	internal energy per unit mass [$=c_v T$]
Q	heating rate per unit mass
R	gas content
c_v	specific heat at constant volume.

Some Climate Processes

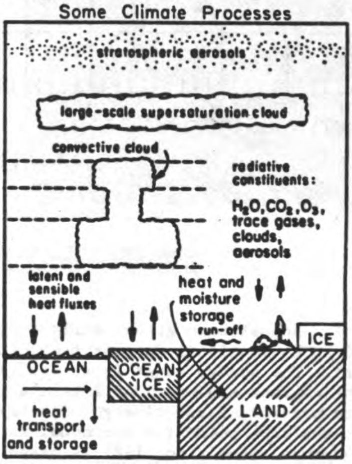


Fig. 6. Schematic illustration of GISS global climate model.

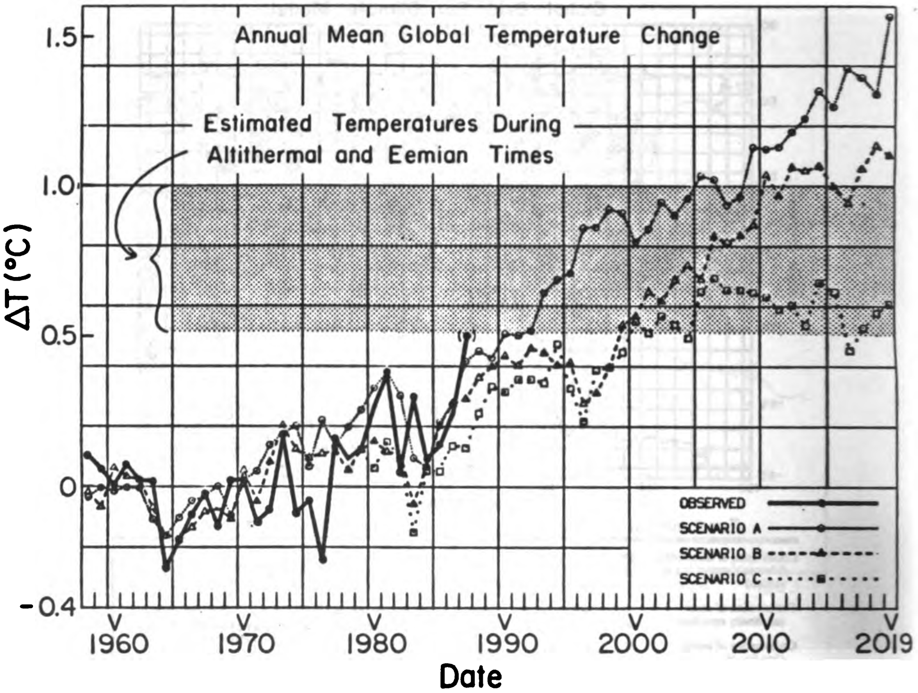


Fig. 7. Annual mean global surface air temperature computed for scenarios A, B and C. Observational data is from Hansen and Lebedeff (J. Geophys. Res., in press). The shaded range is an estimate of global temperature during the peak of the current and previous interglacial periods, about 6,000 and 120,000 years before present, respectively. The zero point for observations is the 1951-1980 mean; the zero point for the model is the control run mean. Observed temperature anomaly for 1987 is based on available station data for January 1 to November 1.

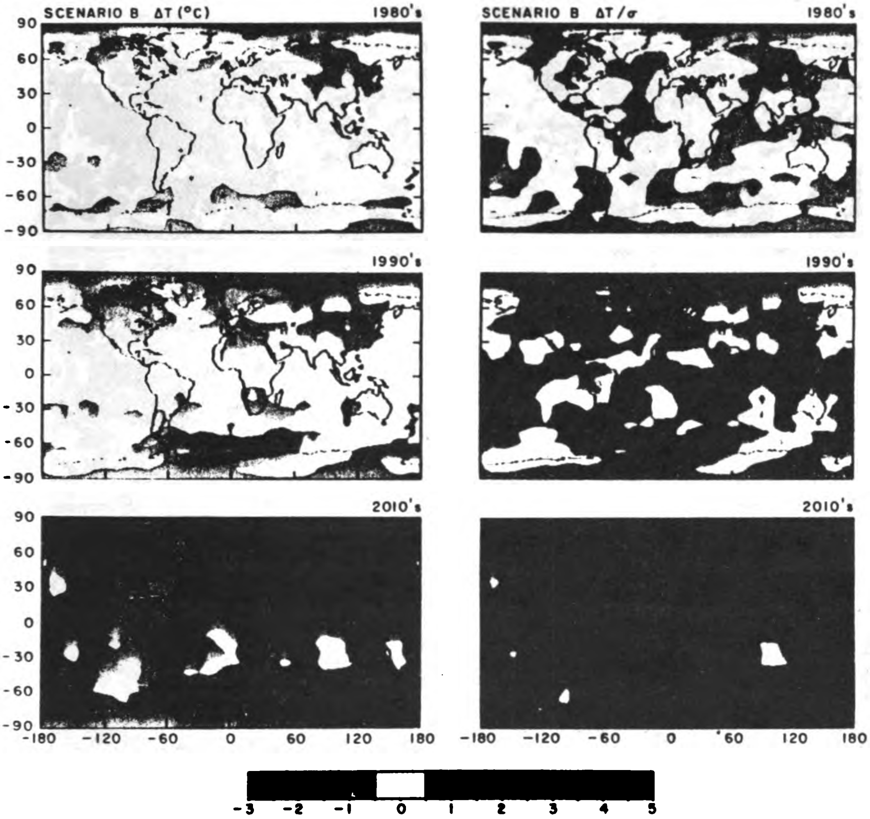


Fig. 8. Left side: decadal mean temperature change obtained for scenario B, relative to the control run, for the decades 1980's, 1990's and 2010's. Right side: ratio of the computed temperature change to the interannual variability of the annual mean temperature in the 100 year control run.

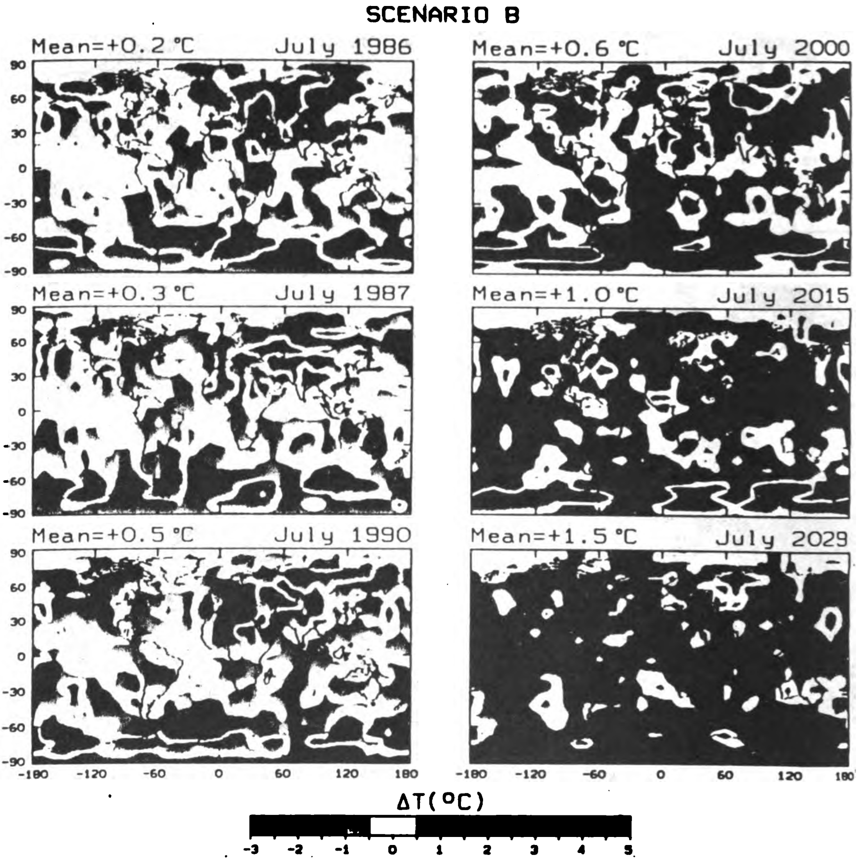


Fig. 9. Simulated July surface air-temperature anomalies for six individual years, compared to 100 year control run with 1958 atmospheric composition.

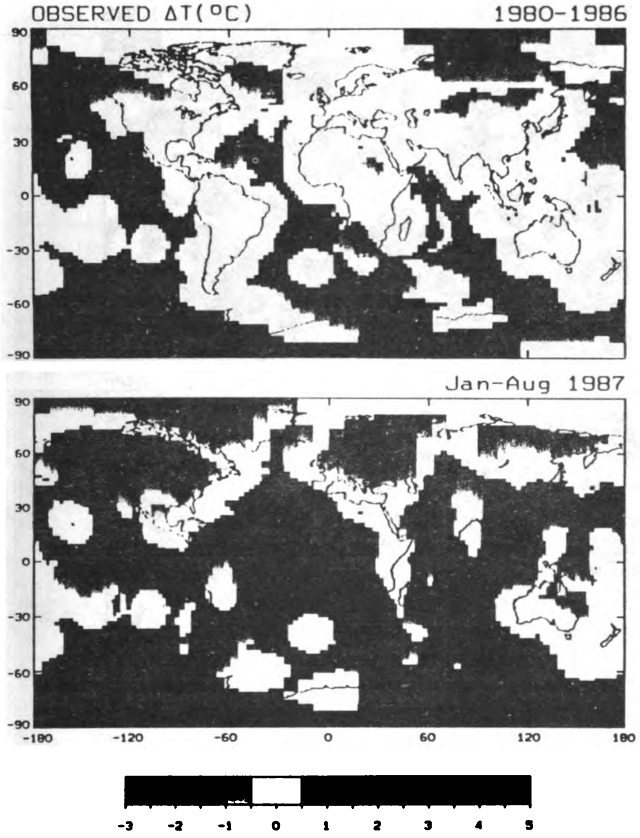


Fig. 10. Observed surface air temperature anomalies in the 1980's, relative to the 1951-1980 climatology of Hansen and Lebedeff (<u>J. Geophys. Res</u>., in press). (a) is the seven-year mean, 1980-1986, and (b) the anomaly for January 1, 1987 to September 1, 1987.

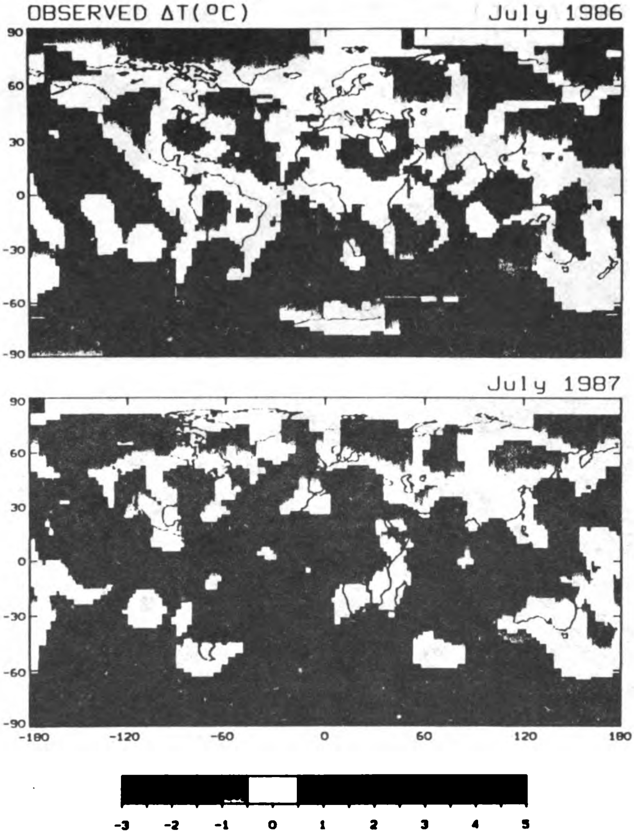


Fig. 11. Observed July surface air temperature anomalies in 1986 and 1987, relative to 1951-1980 climatology.

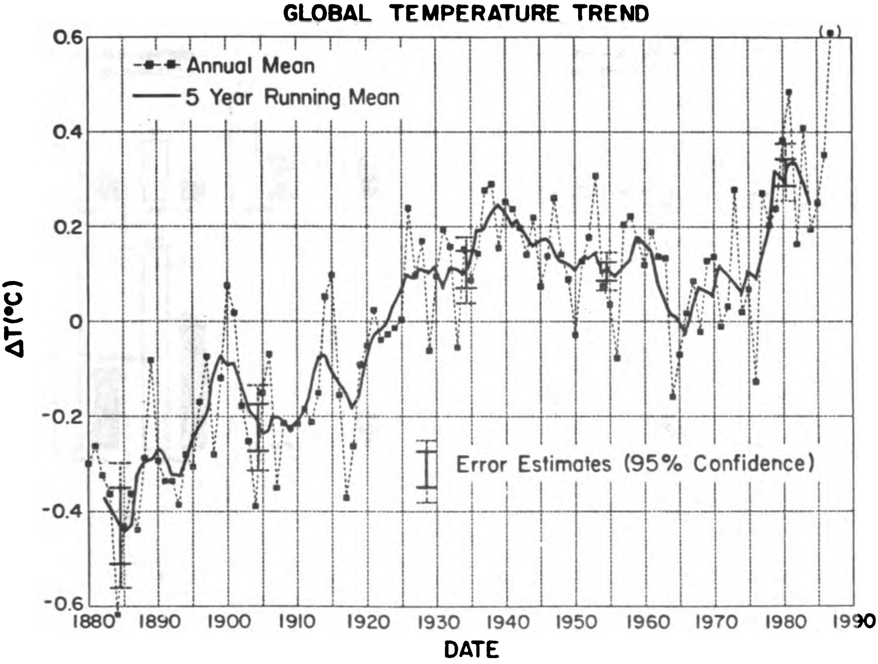
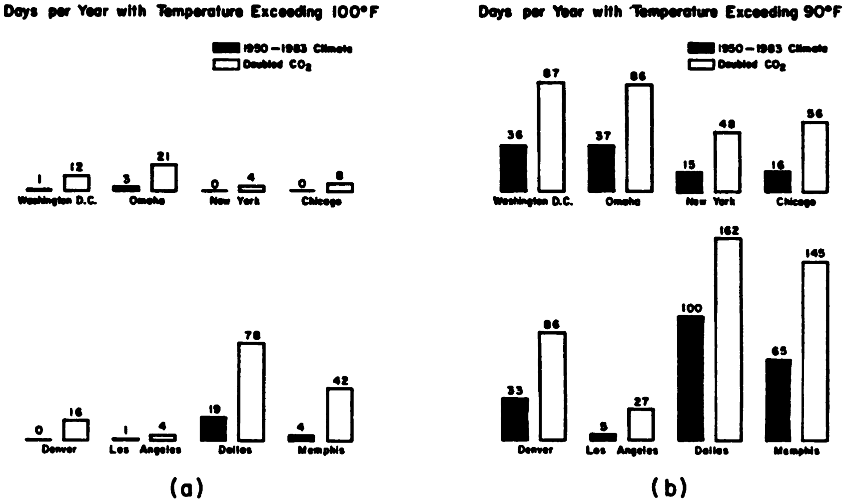


Fig. 12. Global temperature trend for the past century. The 1987 point is an estimate based on the data from January 1 to November 1.



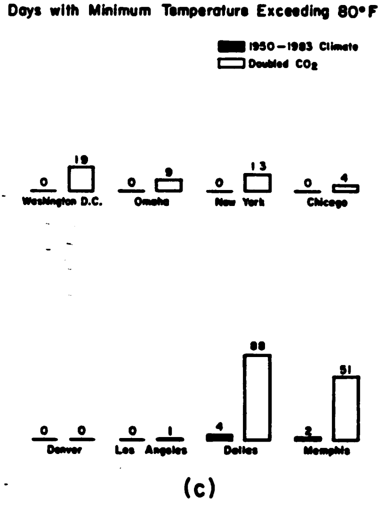


Fig. 13. Annual number of days in several U.S. cities with (a) maximum temperature greater than 100°F, (b) maximum temperature greater than 90°F, and (c) minimum temperature greater than 80°F. The results for doubled CO_2 were generated by adding the warming in a doubled CO_2 climate model experiment to recorded texperatures for 1950-1983.

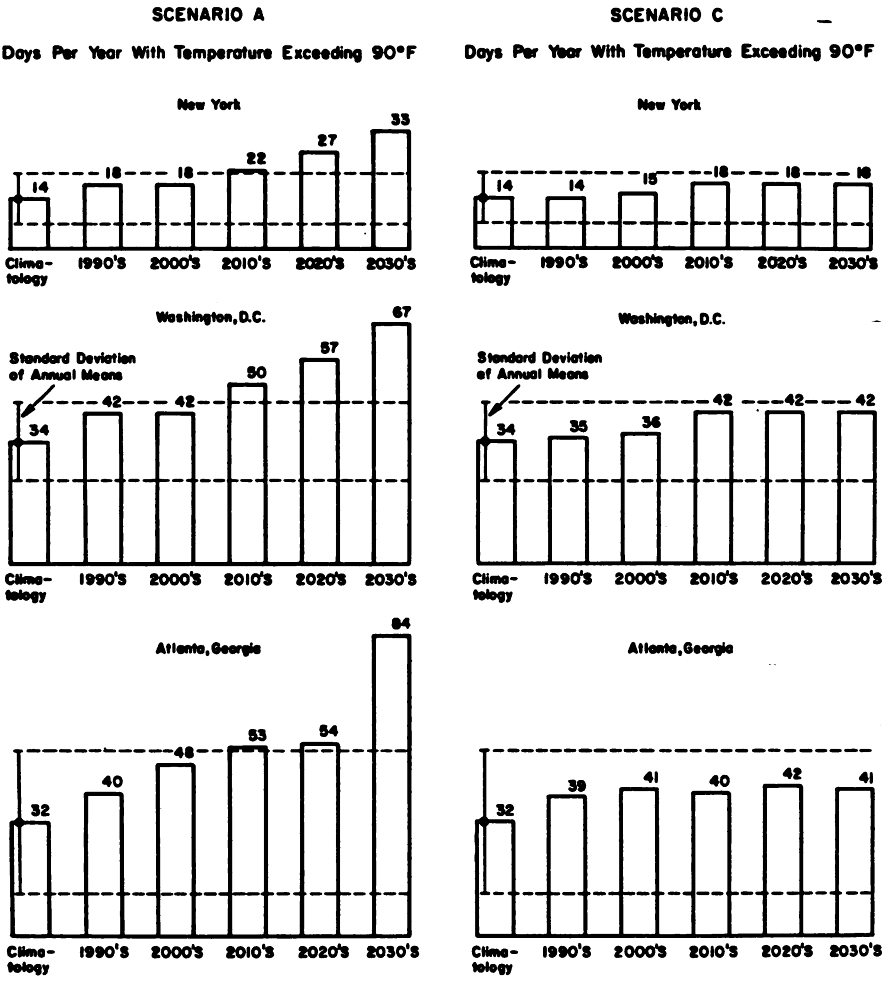


Fig. 14. Annual number of days in three U.S. cities with maximum temperature greater than 90°F. Results are shown by decade for the two extreme trace gas scenarios, A and C.

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SCIENCE

Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing

J. Hansen, G. Russell, A. Lacis, I. Fung, D. Rind, and P. Stone

Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing

Abstract. *The factors that determine climate response times were investigated with simple models and scaling statements. The response times are particularly sensitive to (i) the amount that the climate response is amplified by feedbacks and (ii) the representation of ocean mixing. If equilibrium climate sensitivity is 3°C or greater for a doubling of the carbon dioxide concentration, then most of the expected warming attributable to trace gases added to the atmosphere by man probably has not yet occurred. This yet to be realized warming calls into question a policy of "wait and see" regarding the issue of how to deal with increasing atmospheric carbon dioxide and other trace gases.*

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The abundances of CO_2 and other trace gases in the atmosphere are changing, and it is believed that this change will affect global climate (*1–4*). The global mean surface air warming at equilibrium ($t \to \infty$) expected to result from a doubling of CO_2 (from, say, 300 to 600 ppm) has been estimated (*1, 2*) as

$$\Delta T_{eq}(2 * CO_2) = 3.0° \pm 1.5°C \qquad (1)$$

with the range being a subjective estimate of the uncertainty based on climate modeling studies and empirical evidence for climate sensitivity.

If there were no climate feedbacks (that is, if the atmospheric temperature gradient and all other factors were fixed), the planet would have to warm by

$$\Delta T_0(2 * CO_2) = 1.2° \text{ to } 1.3°C \qquad (2)$$

to restore the radiation balance with space after CO_2 is doubled (*5, 6*). Thus the climate sensitivity (Eq. 1) implies a net climate feedback factor

$$f = 2.4 \pm 1.2 \qquad (3)$$

where f is the ratio of the equilibrium surface air warming to the warming that would have occurred in the absence of any feedbacks.

An important point in evaluating the transient response to a change in CO_2 is that the response time depends on f. This is illustrated by some simple but progressively more realistic systems. First, consider an atmosphereless blackbody planet ($f = 1$). If the equilibrium temperature of this planet suddenly changes a small amount (say, because of a change in the solar constant), it will approach its new temperature exponentially with the blackbody e-folding time (*3*)

$$\tau_b = c/4\sigma T_i^3 \qquad (4)$$

where c is a time-invariant heat capacity per unit of area, σ the Stefan-Boltzmann constant, and T_i the initial temperature.

Second, consider a planet with climate feedback factor f and fixed heat capacity c. This system has the e-folding time (*6*)

$$\tau = f\tau_b \qquad (5)$$

because most climate feedbacks come into play only in response to the climate change (not the change in climate forcing). For example, if CO_2 is doubled, the initial heating is ~4 W m^{-2}, independent of f or $\Delta T_{eq}(2 * CO_2)$. However, if positive feedbacks come into play, such as the water vapor feedback that responds to temperature, the heating decreases more gradually than in the absence of the positive feedback, and the full response is delayed.

In these examples the heat capacity c is in immediate thermal contact with the atmosphere. This is relevant to a planet totally covered by a mixed-layer ocean, if there is negligible heat exchange between the mixed layer and the deeper ocean. For mixed-layer depth $d_0 = 100$ m and $T_i = 255$ K, the effective temperature of the earth, τ_b is ~3.5 years and thus $f \simeq 3$ yields $\tau \simeq 10$ years.

The earth is more complex than this, principally because there is significant heat exchange between the mixed layer and deeper ocean, as recognized in the CO_2 assessment reports (*1, 2, 4*) and earlier (*7*). Also, we must account for the fact that oceans cover only 70 percent of the earth.

The box diffusion ocean model of Oeschger *et al.* (*8*) provides insight into the effect of the deeper ocean on climate sensitivity. This model has a well-mixed upper layer connected to the deeper ocean by Fickian diffusion. The diffusion coefficient k is specified from observed behavior of transient tracers, such as tritium sprinkled on the ocean surface during atomic testing in the 1960's. The d_0 appropriate for time scales greater than 1 year is the global mean annual maximum, ~100 m (*6*). With this d_0, transient tracers imply an effective global k of 1 to 2 $cm^2\ sec^{-1}$ (*6, 8, 9*).

The relation between climate response time, τ, and f can be demonstrated by a scale analysis. Let $d \simeq (k\tau)^{1/2}$ represent depth of penetration of temperature change into the diffusive layer and $D = d_0 + d$ represent total depth of penetration. The surface response time for the box diffusion model is proportional to the depth of penetration of the temperature change. Thus

$$\tau \simeq \frac{D}{d_0}\tau_0 = \frac{D}{d_0} f \tau_b \qquad (6)$$

where τ_0 is the (isolated) mixed-layer response time and τ_b is the blackbody (no feedback) mixed-layer response time. In the limit $k \to 0$, $D \to d_0$ and Eq. 6 reduce to the isolated mixed-layer result (Eq. 5). For large k, $d \simeq (k\tau)^{1/2} >> d_0$ and

$$\tau \simeq \frac{(k\tau)^{1/2}}{d_0} f \tau_b \qquad (7)$$

or, solving for τ

$$\tau \simeq kf^2 \left(\frac{\tau_b}{d_0}\right)^2 \propto f^2 \text{ (large } k\text{)} \qquad (8)$$

Typical values for k (1 $cm^2\ sec^{-1}$) and τ_0 (10 years) yield $d \simeq 170$ m, large enough to be nearer the diffusive regime than the isolated mixed-layer regime. More quantitative calculations, given below, indicate that for these values τ is nearly proportional to f^2 for the box diffusion model.

Before examining this model more quantitatively, we incorporate the influence of continental regions on the heat flux into the ocean surface. The effect of continental regions on climate response times was investigated previously in numerical modeling studies (*10*, *11*). Heating over land areas can, by atmospheric transports, lead to a greater heat flux into the ocean than would occur over the same area of an all-ocean planet. The heat flux (in watts per square meter) into the ocean is proportional to the deviation of the ocean surface temperature from its equilibrium value (*6*):

$$F = \frac{F_0(2 * CO_2)}{\Delta T_{eq}(2 * CO_2)} (\Delta T_{eq} - \Delta T)$$

$$= \frac{F_0(2 * CO_2)}{f \Delta T_0(2 * CO_2)} (f \Delta T_0 - \Delta T) \qquad (9)$$

where ΔT is the ocean surface temperature departure from the $1 * CO_2$ equilibrium reference state, ΔT_{eq} is the equilibrium departure for current atmospheric composition, $F_0(2 * CO_2)$ is the flux into the ocean after CO_2 is doubled and stratospheric temperatures equilibrate but before the ocean temperature responds, and ΔT_0 is the equilibrium temperature change with no feedbacks ($f = 1$)—a measure of the radiative forcing of the climate system for a given change of atmospheric composition, independent of uncertainty in true climate sensitivity.

The proportionality constant in Eq. 9 can be obtained from a $2 * CO_2$ experiment in a three-dimensional (3-D) model with realistic geography. Our 3-D model yields $F_0(2 * CO_2) = 4.3$ W m^{-2} (*5*). On the basis of one-dimensional (1-D) calculations, we estimate that the flux into the surface of an all-ocean planet with this radiation scheme would be 3.5 to 4.0 W m^{-2}. Thus, in this model, heating of continental regions increases the flux into the ocean (per unit of ocean area) by 10 to 20 percent.

The radiative forcing ΔT_0 as a function of CO_2 concentration χ (parts per million), computed with the radiation scheme of our 3-D model (*6*), is fitted by

$$\Delta T_0(\chi) = \ln [1 + 1.2\chi + 0.005\chi^2 + 1.4 \times 10^{-6}\chi^3] \qquad (10)$$

to better than 1 percent for χ between 100 and 1000 ppm. The absolute accuracy of Eq. 10 is estimated to be 10 to 15 percent as a result of uncertainties in CO_2 absorption coefficients and numerical approximations in the modeling (*12*).

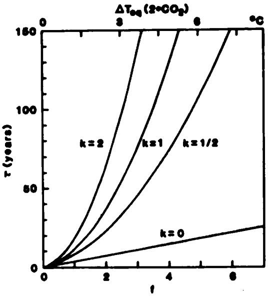

Fig. 1. Ocean surface response time (time to reach $1 - e^{-1}$ of equilibrium response) for the 1-D box diffusion ocean model as a function of climate feedback factor, f, or climate sensitivity to doubled CO_2, $\Delta T_{eq}(2 * CO_2)$ (k is the vertical diffusion coefficient in square centimeters per second; the mixed-layer depth $d_0 = 100$ m). Results depend strongly on k, as illustrated, but only slightly on d_0 for the cases in which $k \geq 0.5$ cm^2 sec^{-1}. Calculations are based on Eqs. 9 and 10, with an instant doubling of CO_2 from 300 to 600 ppm.

Equations 9 and 10 and the box diffusion model for ocean heat storage allow a numerical solution for the temperature trend at the ocean surface for any CO_2 scenario. Let us first consider the idealized case of instant doubling of CO_2 from 300 to 600 ppm. The resulting time required for the mixed layer to reach 63 percent of its equilibrium response, τ, is shown in Fig. 1 as a function of f or $\Delta T_{eq}(2 * CO_2)$. τ is 15 to 25 years for climate sensitivity 1.5°C but 50 to 100 years for climate sensitivity 3°C, if the diffusion coefficient derived from ocean tracers (k = 1 to 2 cm^2 sec^{-1}) is used.

We next let CO_2 increase linearly from 270 ppm in 1850 to 315 ppm in 1958, and thereafter as observed by Keeling *et al.* (*13*). The results (Fig. 2) show that a large part of the equilibrium CO_2 warming is not yet realized, the unrealized fraction depending strongly on f or $\Delta T_{eq}(2 * CO_2)$: If climate sensitivity is 3°C or greater for doubled CO_2, most of the expected equilibrium warming due to the CO_2 increase since 1850 probably has not yet occurred; this must be all the more true for other trace gases, whose greenhouse effect is dominated by chlorofluorocarbons added since 1960 (*14*). This yet to be realized warming calls into question a policy of "wait and see" and "if necessary, make midcourse corrections" regarding the issue of how to deal with increasing atmospheric CO_2 and other trace gases

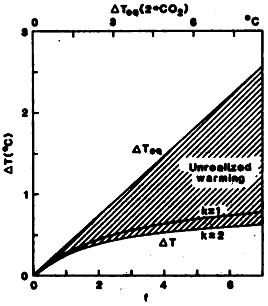

Fig. 2. Ocean surface warming (ΔT) and the equilibrium warming (ΔT_{eq}) due to CO_2 added to the atmosphere in the period 1850 to 1980 for the 1-D box diffusion ocean model as a function of f or $\Delta T_{eq}(2 * CO_2)$.

The Carbon Dioxide Assessment Committee (*4*) attempted to infer climate sensitivity from the Northern Hemisphere surface air warming of 0.5° to 0.6°C in the period 1850 to 1980 by assuming that the warming was due to the increase in CO_2 during that period. With the added assumption that the temperature trends are similar for the ocean surface and hemispheric surface air, they concluded that this evidence indicates a climate sensitivity in the lower part of the 1.5° to 4.5°C range estimated by Charney (*1*) and Smagorinsky (*2*). However, their analysis assumed τ = 15 years, independent of f. As shown above, τ depends strongly, at least linearly, on f. If this dependence is included, along with uncertainties in the actual warming, the 1850 CO_2 abundance, and other variable climate forcings, it is difficult to set an upper limit on climate sensitivity by this method. As shown in Fig. 2, a small uncertainty in ΔT leads to a large uncertainty in f or ΔT_{eq}.

The box diffusion model is a gross simplification of vertical transport in the ocean, and the proportionality of τ to f^2 depends on this diffusive representation as well as on the assumption that a small heat perturbation mixes as a passive tracer. If one used a two-box ocean model with a mixed layer connected to a well-mixed thermocline by a fixed exchange rate, τ would vary linearly with f. However, such a two-box model is less realistic than the box diffusion model, failing to represent the increasing penetration of transient tracers with time. Because their observed penetration does increase with time, τ must increase more strongly than linearly with f for the real ocean. A more precise conclusion depends on obtaining better data on the world ocean circulation, especially the vertical mixing processes.

The assumption that a heat perturbation mixes as a passive tracer may break down as the climatic warming increases. In the ocean model of Bryan *et al.* (*15*), a warm anomaly of 0.5°C penetrates significantly (~25 percent) less than a similar cold anomaly. Furthermore, global warming will be accompanied by changes in evaporation, precipitation, and wind stress over the ocean surface, and possibly by the addition of fresh water from melting ice sheets—all of which may affect the rate of ocean mixing. There is evidence that some mechanisms of ocean overturning are capable of sudden changes (*16*), and the paleoclimate record reveals cases of large warming within periods of no more than several decades (*16, 17*). Thus we cannot exclude the possibility that the climate may at some point undergo a rapid transition to the equilibrium climate for current atmospheric composition.

The existence of unrealized warming complicates the CO_2 and trace gas issue and limits the near-term effectiveness of reductions in greenhouse gas emissions. The strong dependence of this unrealized warming on the equilibrium climate sensitivity emphasizes the importance of narrowing uncertainties about the strength of climate feedback processes. This will require better understanding of many components of the climate system including clouds, the cryosphere, biogeochemical cycles, ocean mixing, vegetation, and the land surface.

References and Notes

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12. Our 3-D model [*J. Atmos. Sci.* 111, 609 (1983)] averages gaseous absorption over broad ranges for computational efficiency. This radiation scheme yields a forcing $\Delta T_0 = 1.2°C$ for doubled CO_2 (300 to 600 ppm) and an initial flux $F_0 = 4.3$ W m^{-2} into the ocean in the 3-D model. A more detailed radiation scheme with fine spectral resolution yields $\Delta T_0 = 1.26°C$ for 1-D calculations with a global mean atmospheric profile and would be expected to increase F_0 proportionately, without affecting τ. The latter radiation scheme has been compared with a wide range of other models, including line-by-line calculations, with results agreeing within ~10 percent [F. M. Luther and Y. Fouquart, *WMO Rep. WCP-93* (1984)]. Other published values for ΔT_0 are 1.33°C (*4*) and 1.3°C [V. Ramanathan, *J. Atmos. Sci.* 38, 918 (1981)].
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GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

HEARINGS

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

ONE HUNDREDTH CONGRESS

FIRST SESSION

ON THE

GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

NOVEMBER 9 AND 10, 1987

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GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

MONDAY, NOVEMBER 9, 1987

U.S. Senate,
Committee on Energy and Natural Resources,
Washington, DC.

The committee met, pursuant to notice, at 9:35 a.m., in room SD-366, Dirksen Senate Office Building, Hon. Timothy E. Wirth, presiding.

OPENING STATEMENT OF HON. TIMOTHY E. WIRTH, U.S. SENATOR FROM COLORADO

Senator **Wirth**. The committee will come to order. Gentlemen, thank you very much for being with us this morning. I bring you greetings from Senator Johnston who is, as you know, one of the three Senate negotiators in the budget process. He is hoping to be able to drop by this morning but those negotiations are picking up in earnest. So, he sends you his thanks for appearing here and looks forward to seeing your statements.

When we originally scheduled this hearing, we thought that the Senate was going to be in session on Mondays in November. It now turns out that we are not, so we may have sparse attendance today. However, the purpose of this hearing, of course, is to develop a record.

As John Firor has told me, the science of the greenhouse effect is evolving rapidly. It has received broad consensus on the scientific community, and scientists are telling us that this is a very serious issue.

We are certainly hoping that we are going to be able to change that last phenomenon with the beginnings of your testimony today.

A number of members of the committee will have statements that they want to have included in the record, and those will be included in full in the record.

[The prepared statements of Senator Johnston and Senator Wirth follow:]