The Greenhouse Effect: Projections of Global Climate Change *

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SUMMARY

We present projections of global climate during the next several decades, based principally on climate model simulations in which atmospheric CO_2 and trace gases increase steadily at rates estimated from observations. This is the first time that a global climate model has been used for simulating the climate effects of the transient growth of greenhouse gases, and as such it permits an estimate of when the greenhouse effect should begin to be evident above the level of natural climate variability. We emphasize that a number of caveats must be attached to the climate model results. But we also stress that the climate sensitivity of our model has been extensively compared to the sensitivity of other models and is consistent with available empirical evidence from past climate changes.

Our presentation is organized as a response to a letter from Chairman John Chafee of the United States Senate Subcommittee on Environmental Pollution of the Committee on Environment and Public Works who requested testimony at a hearing on the greenhouse effect on June 10, 1986. Specifically, his letter asked that the following topics be addressed:

- The nature of our work in modeling greenhouse climate effects
- How we test the models to determine their validity

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- The relative contribution of different greenhouse gases to possible future climate change

- The temperature changes predicted for the next few decades and the next century, assuming some reasonable growth in trace gases

- How the predicted temperatures compare to past temperatures experienced on the earth

- How temperature changes of the magnitude predicted might alter the number of days with temperatures above a given limit for Washington, D.C. and other U.S. cities

- Further evidence needed to confirm and quantify the greenhouse theory.

GLOBAL CLIMATE MODELING

In principle, global climate models are quite simple. For example, in our model (Hansen et al. 1983, hereafter referred to as paper 1) the earth is divided into 'gridboxes' as shown in Figure 1, and each gridbox is divided vertically into a number of layers, typically nine, in the atmosphere. Similarly, the ground or ocean in each gridbox is divided into several vertical layers. The mathematical equations describing the fundamental conservation laws of physics are solved numerically for each gridbox by a computer program, which calculates the transfer of mass, energy, and momentum from one box to another and also simulates physical processes within the boxes which represent sources and sinks of these substances.

Such global climate models, or GCMs, are able to reproduce the general features of the earth's climate. Climate variables such as temperature, winds, and storm tracks, and their variations from season to season, from latitude to latitude, and from continent to ocean, are represented realistically, at least in a qualitative sense. But the models are not sufficiently realistic to portray accurately regional patterns of precipitation, ocean currents, and other processes that are important for determining the practical consequences of climate trends because of greenhouse warming. Recent evidence that the large-scale ocean circulation may have undergone dramatic changes in the past (Broecker, Peteet, and Rind 1985) is of special concern; the representations of oceans in current GCMs are not sufficiently realistic to predict such phenomena.

Improvement of the climate models will depend especially upon better knowledge of physical processes occurring within the climate model gridboxes. These processes are represented by submodels or "parameterizations." For example, Figure 1b schematically illustrates convective clouds associated with convective transport of moisture, heat, and momentum between model layers. Although there have been major field experiments to study convection clouds, substantial work is needed to provide more realistic submodels for use in GCMs. Another example, one which is beginning to receive greater attention, concerns the role of vegetation and soil processes in the transfer of moisture, heat, and momentum between the earth's surface and the atmosphere. As a final example, we must have a better understanding of small-scale ocean

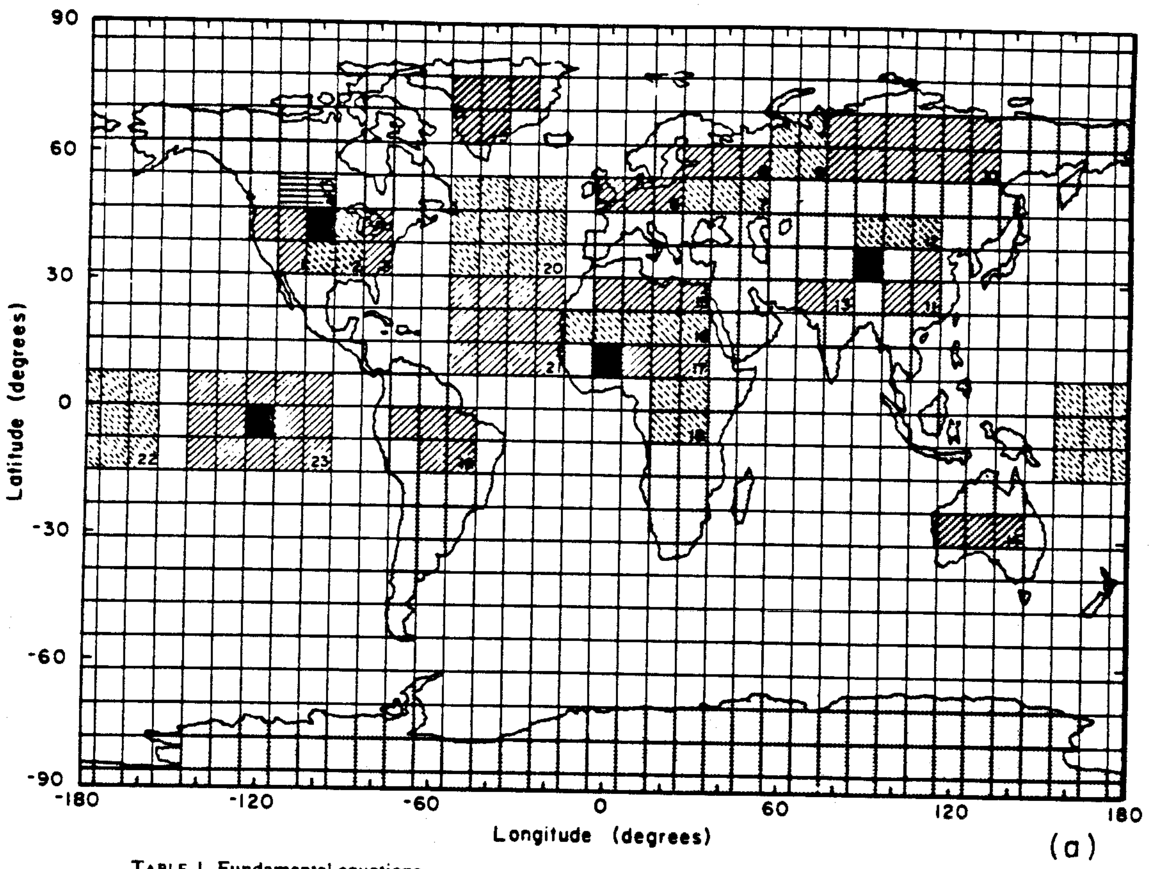


TABLE 1. Fundamental equations.

Conservation of momentum: (Newton's second law of motion)	$\frac{d\mathbf{V}}{dt} = -2\mathbf{\Omega} \times \mathbf{V} - \rho^{-1}\nabla p + \mathbf{g} + \mathbf{F}$	(T1)
Conservation of mass: (continuity equation)	$\frac{d\rho}{dt} = -\rho\nabla \cdot \mathbf{V} + C - D$	(T2)
Conservation of energy: (first law of thermodynamics)	$\frac{dI}{dt} = -p\frac{d\rho^{-1}}{dt} + Q$	(T3)
Ideal gas law: (approximate equation of state)	$p = \rho RT$	(T4)

Notation

$\mathbf{V}$	velocity relative to rotating earth
t	time
$\frac{d}{dt}$	total time derivative $\left[= \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right]$
$\mathbf{\Omega}$	planet's angular rotation vector
ρ	atmospheric density
$\mathbf{g}$	apparent gravity [=true gravity $- \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r})$]
$\mathbf{r}$	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.

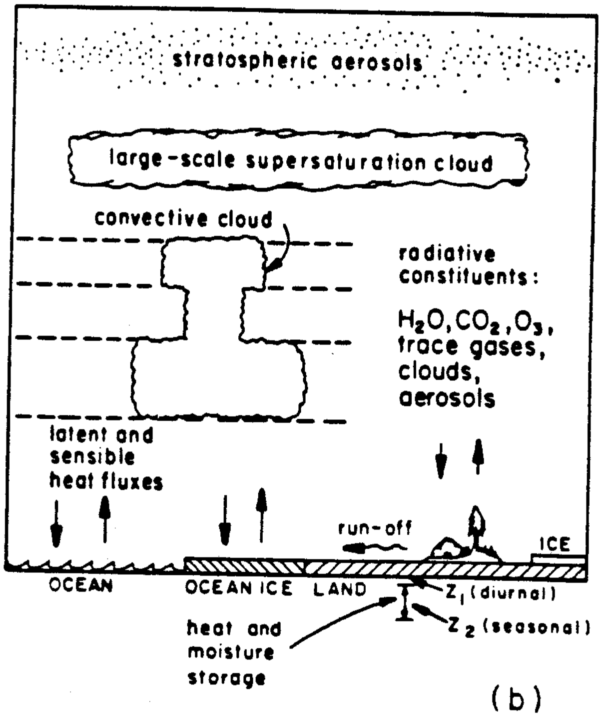


Figure 1.

mixing before we can develop an accurate model of global ocean circulation and currents.

A principal conclusion is that decades of research are likely to be required to improve climate models to the point that they can be used to predict local and regional climate changes with a high degree of confidence. Such improvements will be possible only if appropriate observations of the climate system and climate processes are carried out. In the meantime, climate models can provide a useful indication of the possible magnitude of future climate trends, although the results must be accompanied by appropriate explanations and caveats, especially the results at smaller scales.

Finally, we would like to stress one key characteristic of both climate model results and real-world climate, i.e., natural climate variability. Figure 2 illustrates the global mean temperature in a 100-year control run of our 3-D GCM. It can be seen that the temperature fluctuates, both from year to year and with decadal trends, even though the amount of atmospheric CO_2 and other climate "forcings" are unchanging in the model. Such variability or "noise" is a natural characteristic of the climate system. Although this phenomenon is captured by the governing fundamental equations in the climate model, individual fluctuations are not predictable. Thus, for any climate trend to be detected, it must exceed the level of natural climate variability.

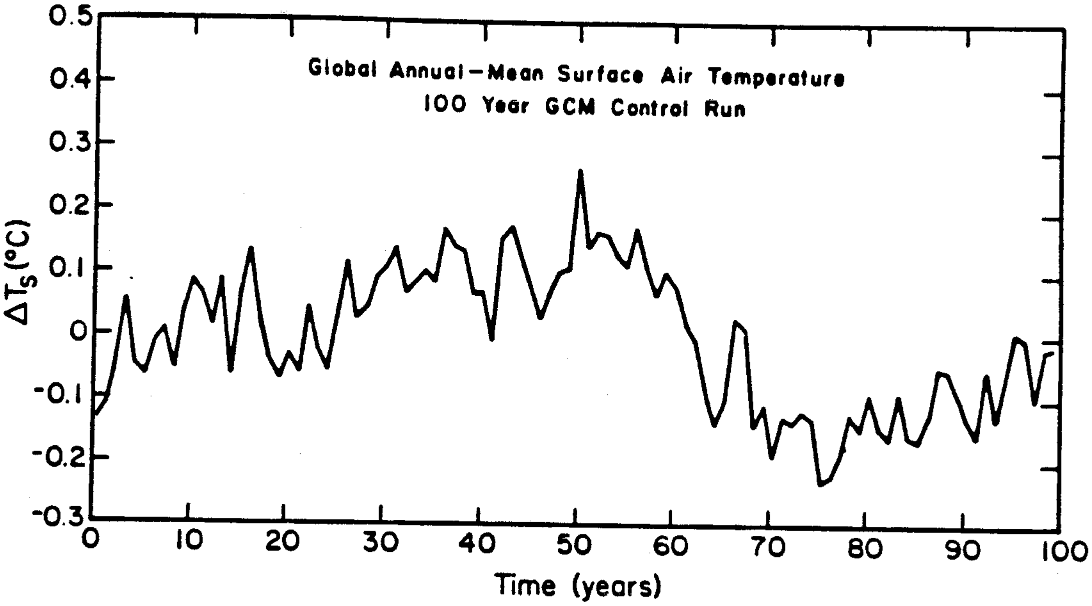


Figure. 2. Global-mean annual-mean surface air temperature in the 100-year control run with the GISS global climate model with predicted ocean temperature. Atmospheric CO_2, trace gases, and aerosols are unchanging during this run. The ocean-mixed layer has the observed seasonal and geographical depth variations and no exchange of heat with the deeper ocean.

TESTS OF CLIMATE MODELS

A good overall test of the greenhouse effect is provided by examining the climates of several planets--Mars, Earth, and Venus--which have a wide range of abundances of atmospheric greenhouse gases. These planets are warmer than they would be if they were simply in blackbody equilibrium with the energy absorbed from the sun. The observed greenhouse warmings are a few degrees on Mars, about 35 degrees on Earth, and several hundred degrees on Venus. The magnitude of these warmings is in excellent agreement with the greenhouse theory and simple climate models.

Another test, of more direct relevance, is provided by prehistoric climate variations on Earth. This test is only recently beginning to be exploited. The climate of the Earth has fluctuated between ice ages and interglacial warm periods several times during the past few hundred thousand years. It has been realized for more than a decade that small variations in the earth's orbital characteristics about the sun were the 'pacemakers' of the 10,000- to 100,000-year climate changes (Hays et al. 1976), but the mechanisms by which global temperature changes were produced remain uncertain. Recently it has been discovered that the atmospheric CO_2 abundance fluctuated along with ancient climate, and was thus a probable agent producing the global temperature changes. This inference of past CO_2 warming allows an empirical evaluation of climate sensitivity to a CO_2 change.

In particular, the paleoclimate record indicates that a CO_2 change of 50-100 parts per million (ppm) (Oeschger et al. 1984) is associated with a global mean temperature change of 4°-5°C (CLIMAP Project 1981). The global radiative forcing (ΔT_0) due to this CO_2 change, i.e., the surface temperature change which would occur if there were no climate "feedback" processes, can be accurately computed and is

$$\Delta T_o \sim 0.5^\circ C. \tag{1}$$

Thus, under the assumption that the CO_2 change is the dominant forcing for the global temperature change, the total climate feedback factor f, defined by

$$\Delta T = f \Delta T_o, \tag{2}$$

is $f \sim 10$ for the recent glacial-to-interglacial climate changes. Physical processes contributing to f have been analyzed (Hansen et al. 1984, hereafter referred to as paper 2) and it has been shown that a substantial part of the total feedback factor is due to the growth and decay of large continental ice sheets, a process which is not significant on the time scale of the next few decades. The feedback factor inferred from the paleoclimate data for processes that are relevant to a climate change on decadal time scales is $f \sim 2\text{-}4$.

The paleoclimate evidence thus indicates that if atmospheric CO_2 were doubled from, say, 300 ppm to 600 ppm, and the climate system were allowed to come to a new equilibrium, the earth would warm by

$$\Delta T(2*CO_2) \sim (2^\circ\text{-}4^\circ C) * \Delta T_o \sim 2.5^\circ\text{-}5^\circ C, \tag{3}$$

where $\Delta T_o \sim 1.25$ is the no-feedback radiative forcing due to doubling atmospheric CO_2.

The climate sensitivity inferred from paleoclimate evidence is reasonably consistent with the climate sensitivity estimated by several National Academy of Science studies (Charney et al. 1979; Smagorinsky et al. 1982),

$$\Delta T(2*CO_2) = 3^o \pm 1.5^oC, \qquad (4)$$

which was based mainly on intercomparison and analysis of several different climate model studies. Thus there is general agreement about the magnitude of global climate sensitivity, but the uncertainty in its value is at least a factor of two.

Despite all the above evidence, the one truly convincing test of the models must be a comparison of the models' predictions with the observed response of the earth's climate to the present anthropogenically induced growth of atmospheric CO_2 and trace gases. Thus, we illustrate in Plate 2 the temperature changes that have occurred during the past century, a time during which CO_2 has increased from about 280 ppm to 340 ppm and several other trace gases have also increased.

The geographical patterns of temperature change (Plate 2a) contain a large amount of natural variability, as well as errors in regions where there are few stations and short records. The influence of the climate 'noise' and incomplete station coverage is reduced by averaging results over all longitudes. Plate 2b shows the resulting temperature trends for the period 1880-1984 as a function of latitude.

Several conclusions follow from the data illustrated in Plate 2. Most of the earth has warmed in the past 100 years, but there is a great amount of local variability. The global mean warming since 1880 is about 0.6°C (1°F), with both hemispheres warming by about that amount. Although the earth was about as warm in the 1930s and 1940s as it is in the 1980s, the earlier warming was more concentrated in the high latitudes of the Northern Hemisphere, while the recent warming is more global.

The global warming of 0.6°C in the past century is of the magnitude expected as a result of increasing CO_2 and trace gases. It is difficult to make a more definitive statement than that, in part because the greenhouse forcing is time dependent (most of the growth coming in the past 25 years) and the climate system has a finite response time, probably several decades (paper 2 and Hansen et al. 1985), so that only a part of the eventual warming due to these added gases has occurred as yet. Also, a warming of 0.6°C is not particularly large compared to climate fluctuations that have occurred in the past millenium, as illustrated below.

We show below that the expected greenhouse climate signal is rising rapidly and should soon rise well above the level of natural variability. This would provide strong empirical verification of the greenhouse effect.

PREDICTED TEMPERATURE CHANGES

The estimated contributions of different greenhouse gases to climate forcing is illustrated in Figure 3 for different periods. The CO_2 contribution is known accurately, within about 10 percent. The contributions of chlorofluorocarbons CCl_3F (F_{11}) and CCl_2F_2 (F_{12}), compounds which are entirely man made, are also known accurately. The CH_4 greenhouse contribution is less certain; there is some recent evidence suggesting that the CH_4[1] growth rate we assumed (0.6 percent per year in the 1960s, 1 percent per year[1] in the 1970s, and 1.5 percent year in the 1980s) may be too high for the 1980s and perhaps too low for the 1960s (Rasmusson and Khalil 1986; Rinsland et al. 1985; Blake and Rowland 1986). The O_3 and stratospheric H_2O changes, based on a chemical model, are very uncertain and are best described as hypothetical; indeed, recent spotty observations of O_3 profiles do not support a positive greenhouse forcing due to changing O_3 (Lacis et al. 1986). Despite uncertainties about the trends of some of the gases, two firm conclusions can be made:

- In the past few decades the rate of increase of greenhouse forcing of the climate system has increased rapidly; it is now three to ten times greater than during the previous century, 1850-1960.

- Non-CO_2 greenhouse gases now add to the greenhouse effect at a rate comparable to that of CO_2.

We have carried out the first GCM simulations of climate trends due to the current changes of atmospheric CO_2 and trace gases. One disadvantage of presenting recent research results is that we cannot claim that the results have been confirmed by other climate modeling groups. However, the sensitivity of our global climate model has been compared and found to be similar to that of other climate models at the NSF National Center for Atmospheric Research (Washington and Meehl 1984) and the NOAA Geophysical Fluid Dynamics Laboratory (Manabe and Broccoli 1985; Wetherald and Manabe 1986). Thus we expect that the general conclusions discussed below would not be changed if the models of these other laboratories were used, provided that similar basic assumptions were made, for example, with regard to trace gas growth rates and ocean heat uptake.

The global climate model employed for these simulations is our model II documented in paper 1, which has an equilibrium global mean sensitivity of 4.2°C for doubled CO_2 as documented in paper 2. For these transient experiments the ocean mixed layer depth is based on climatology, including geographical and seasonal variations. Heat capacity of the ocean beneath the mixed layer is included by treating a heat perturbation as a passive tracer which can diffuse into the deeper ocean; the diffusion coefficient varies geographically as a function of the climatological local stability beneath the mixed layer, according to the empirical relation given in paper 2. Horizontal ocean heat transports are fixed as described in paper 2.

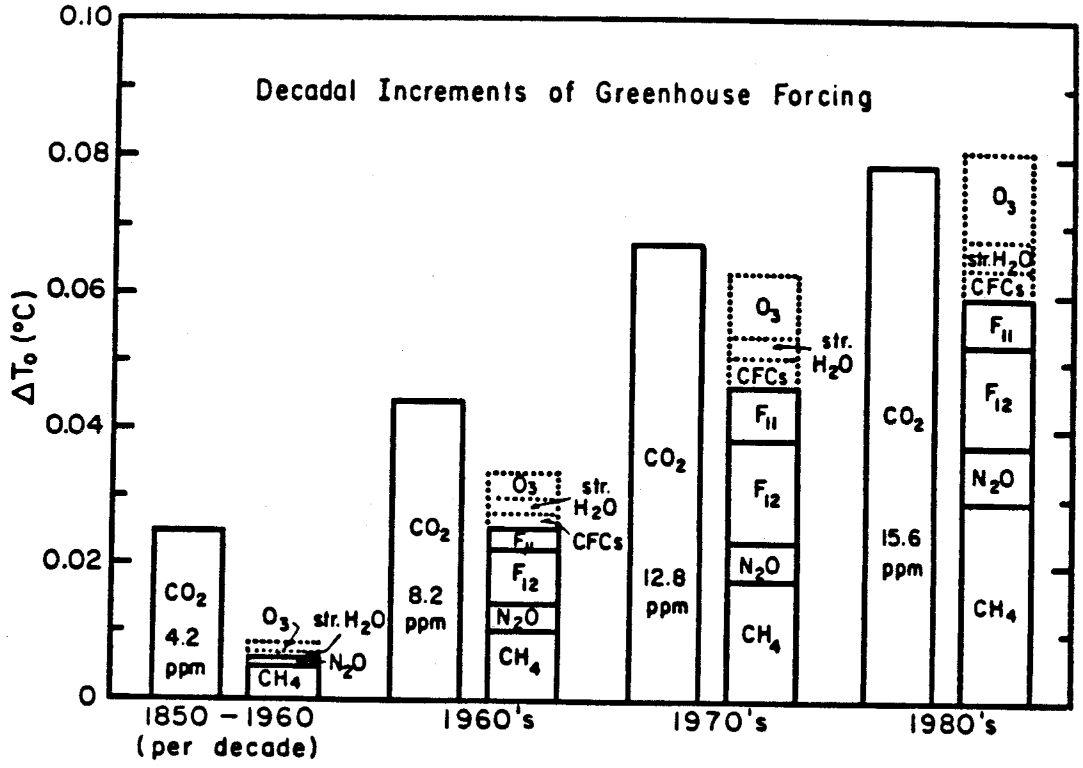


Figure 3. Decadal additions to global mean greenhouse forcing of the climate system. ΔT_0 is the computed temperature change at equilibrium for the estimated decadal increase in trace gas abundances, with no climate feedbacks included. Multiply ΔT_0 by the feedback factor f to get the equilibrium surface temperature change including feedback effects. Most of the estimated trace gas increases are based on measurements. However, the O_3 and stratospheric H_2O trends (dotted bars) are based principally on 1-D model calculations of Wuebbles et al. (1983).

Our GCM simulations begin in 1958, when CO_2 began to be monitored accurately by C.D. Keeling, and extend through the present into the future. We consider two scenarios, A and B, to allow for uncertainties about past trace gas changes and future CO_2 and trace gas changes. Scenario B includes only five greenhouse gases that have been measured reasonably well (CO_2, F_{11}, F_{12}, CH_4, N_2O) and it assumes that their growth rates will decrease rapidly during the next few decades. Scenario A includes an allowance to approximate the greenhouse forcing of the several other hypothesized gases in Figure 3, and it allows presently estimated growth rates to continue. We do not contend that Scenarios A and B represent extreme possibilities; however, they do help us to estimate how sensitive the conclusions are to assumptions about the climate forcings.

Scenario A achieves a radiative forcing equivalent to that for doubled CO_2 about 40 years from now, in the late 2020s. Scenario B achieves this level of forcing in about 2060. The more detailed trace gas scenario of Ramanathan et al. (1985) is close to Scenario A (see Figure 4). Finally, we note that both scenarios include some additional radiative forcing due to volcanic aerosols, a forcing that tends to cool the surface. The aerosol forcing is the same in the two scenarios for the period 1958-1986, with two significant coolings: 1963-66 (Mt. Agung) and 1982-85 (El Chichon). Scenario B assumes that the mean aerosol forcing in the future will be similar to that in the period 1958-1966, a period of active volcanism, while Scenario A assumes a negligible future volcanic forcing, as was the case for the period 1910-1960.

Global maps of temperature changes obtained in the GCM climate experiments are shown in Plate 3. The detailed geographical patterns of these changes are not to be taken seriously in view of the limitations of current GCMs mentioned above and the gross assumption about ocean heat transports. However, some of the large-scale features are more likely to be meaningful.

The warming in Scenario A at most midlatitude Northern Hemisphere land areas such as the United States is typically 0.5°-1.0°C (1°-2°F) by the decade 1990-2000 (Plate 3a) and 1°-2°C (2°-4°F) by the decade 2010-2020 (Plate 3b). Even in the latter decade the warming is much less than the equilibrium response to doubled CO_2 (Plate 3c) which has a warming of about 5°C in the United States. At all future times the largest temperature changes are in regions of sea ice and the smallest are at low and middle latitude ocean areas.

The global mean temperatures computed by the model are compared to observations in Figure 5 for the period 1958 to the present. In this period the greenhouse forcing of Scenarios A and B differ only by about 10 percent. It is apparent that the observed temperatures and the model results are consistent during this period. But the natural variability of temperature in both the real world and the model are sufficiently large that we can neither confirm nor refute the modeled greenhouse effect on the basis of current temperature trends.

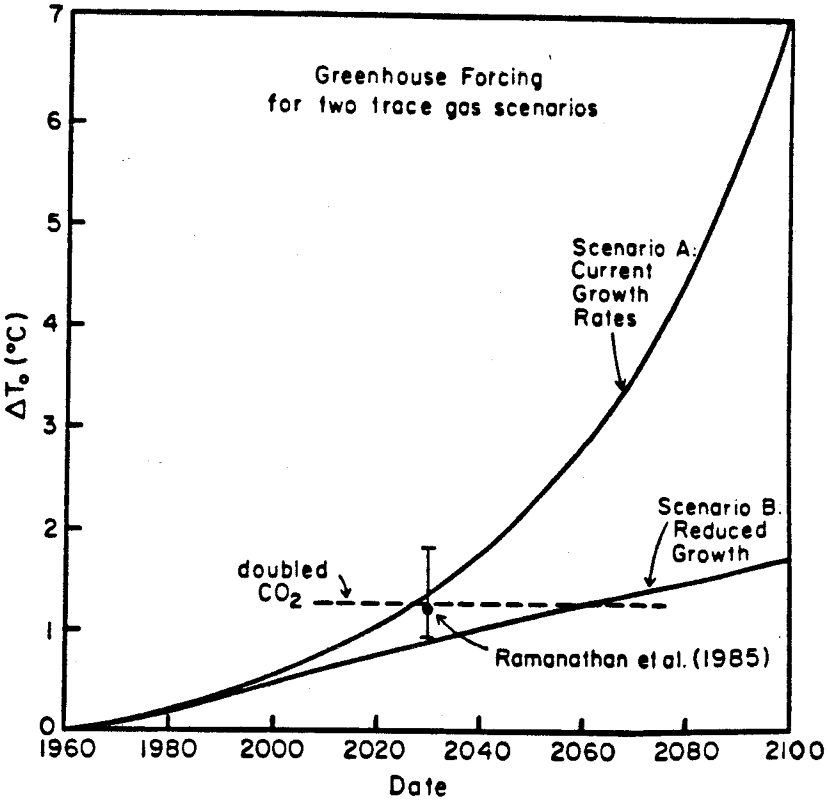


Figure 4. Greenhouse forcing for two trace gas scenarios. ΔT_o is the equilibrium warming with no climate feedbacks. Scenario B includes only CO_2, CH_4, N_2O, F_{12}, and F_{11}, and it assumes that their growth rates will decrease rapidly in the next 25 years. Scenario A includes an allowance for other trace gasses hypothesized in Figure 3 and it allows current growth rates to continue indefinitely.

In Scenario A CO_2 increases as observed by Keeling for the interval 1958-1984 and subsequently with a 1.5 percent growth of the annual increment. CCl_3F and CCl_2F_2 emissions are from reported rates to date and assume 3 percent per year^{-1} increased emission in the future, with atmospheric lifetimes for the gases of 75 and 150 years, respectively. CH_4 increases from 1.4 parts per billion in 1958 at a rate of 0.6 percent per year^{-1} until 1970, 1 percent per year^{-1} in the 1970s and 1.5 percent per year^{-1} thereafter. N_2O increases according to the semi-empirical formula of Weiss (1981), the rate being 0.1 percent per year^{-1} in 1958, 0.2 percent per year^{-1} in 1980, 0.4 percent per year^{-1} in 2000 and 0.9 percent per year^{-1} in 2030. Potential effects of several other trace gases (such as O_3, stratospheric H_2O, and chlorine and fluorine compounds other than F_{11} and F_{12}) are approximated by multiplying the CFC amount by the factor 2.

In Scenario B the growth of the annual increment in CO_2 is reduced from 1.5 percent today to 1 percent in 1990, 0.5 percent in 2000 and zero in 2010. The growth in annual emissions of CCl_3F and CCl_2F_2 is reduced from 3 percent today to 2 percent in 1990, 1 percent in 2000 and 0.5 percent in 2000. N_2O increases are based on Weiss' (1981) formula, but the parameter specifying annual growth in anthropogenic emissions decreases from 3.5 percent today to 2.5 percent in 1990, 1.5 percent in 2000 and 0.5 percent in 2010. No increases are included for other chlorofluorocarbons, ozone, stratospheric water or any other gases.

On the other hand, it is also apparent from Figure 5 that the predicted greenhouse warming for Scenario A rises above the level of natural variability by the 1990s. The standard deviation of the five year smoothed global temperature during the past century is $\sigma \sim 0.2^{\circ}C$. Thus a global warming of 0.6°C, compared to, say, the 1958-1980 mean temperature, would be a 3σ effect, significant at the 99 percent confidence level. The model predicts that such a warming will be achieved in the 1990s.

Indeed, the model predicts a temperature level in the next 15 years that has not existed on earth in the past 100,000 years, as illustrated below. In view of the significance of such conclusions, we stress here the principal caveats which must accompany the result:

- The model sensitivity is 4.2°C for doubled CO_2. Emergence of the warming signal above the level of natural climate variability will be delayed if the true sensitivity is less than that.

- The projection is based on Scenario A. If Scenario B is more realistic, emergence of the warming signal will be delayed. We estimate that Scenario B would delay the emergence of the signal by several years, but a more quantitative statement requires extension of the Scenario B simulation.

- Other major climate forcings that tend to counteract the greenhouse warming may occur during the next several years. As one example, satellite measurements indicate that solar irradiance decreased in the period 1980-1984 (cf. references in Kerr 1986) at a rate that would approximately cancel the increase in greenhouse forcing during the same period. Although decreases in solar irradiance are probably cyclical and must be balanced by comparable increases over a time scale of several decades, it is possible that a decreasing trend could continue for several more years. As a second example, an unusual increase in volcanic activity could conceivably counteract the greenhouse warming for as long as a decade or so: Scenario B contains a substantial amount of volcanic aerosols, similar to the amount in the volcanically active period 1958-1985, but it is possible to have a still greater level of volcanic activity.

- There may be crucial climate mechanisms that are omitted or poorly simulated in current climate models. An example is changes in ocean circulation, such as the formation of deep water (Bennett et al. 1985). If the rate of deep water formation is reduced, it is even possible that the North Atlantic and Europe may cool while most of the world is warming. A change in ocean circulation would also raise the possibility of a more rapid transition to a warmer climate, if it reduced the effective thermal inertia of the ocean and thus reduced the climate response time (paper 2; Hansen et al. 1985).

COMPARISON WITH PAST TEMPERATURES

Global temperature changes are illustrated in Figure 6 for the past century, millenium, and 25,000 years and in Figure 7 for the past 150,000 years. The global mean temperature has varied by about 0.5°C in the past century and 5°C in the past several hundred thousand years (National Academy

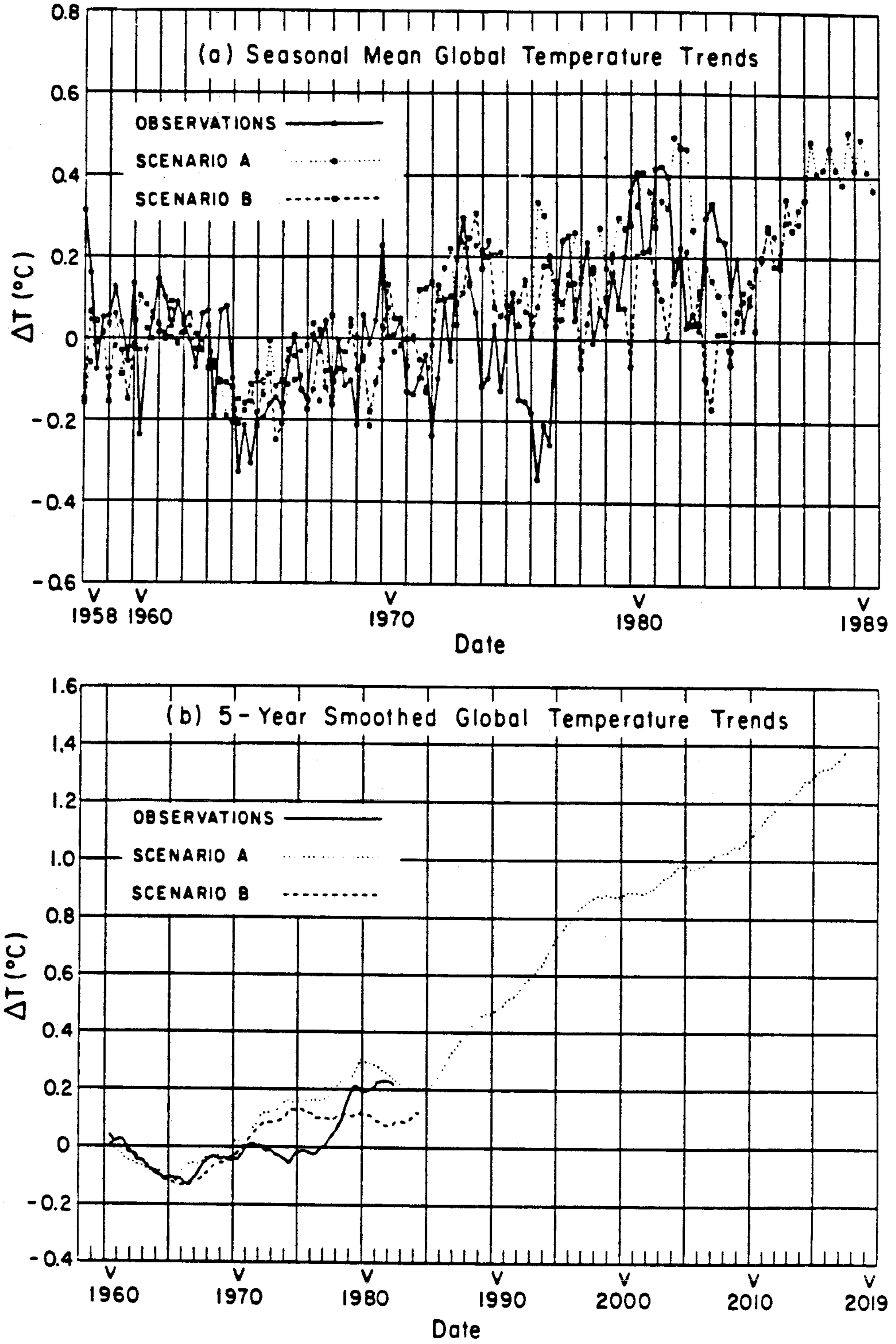


Figure 5. Global temperature trends from observations (solid line) and from calculations with the GISS global climate model. Part (a) shows the temperature anomalies plotted each season (December-January-February, March-April-May, etc.). Part (b) shows the 5-year smoothed results. Simulations have only been carried out into the future for Scenario A.

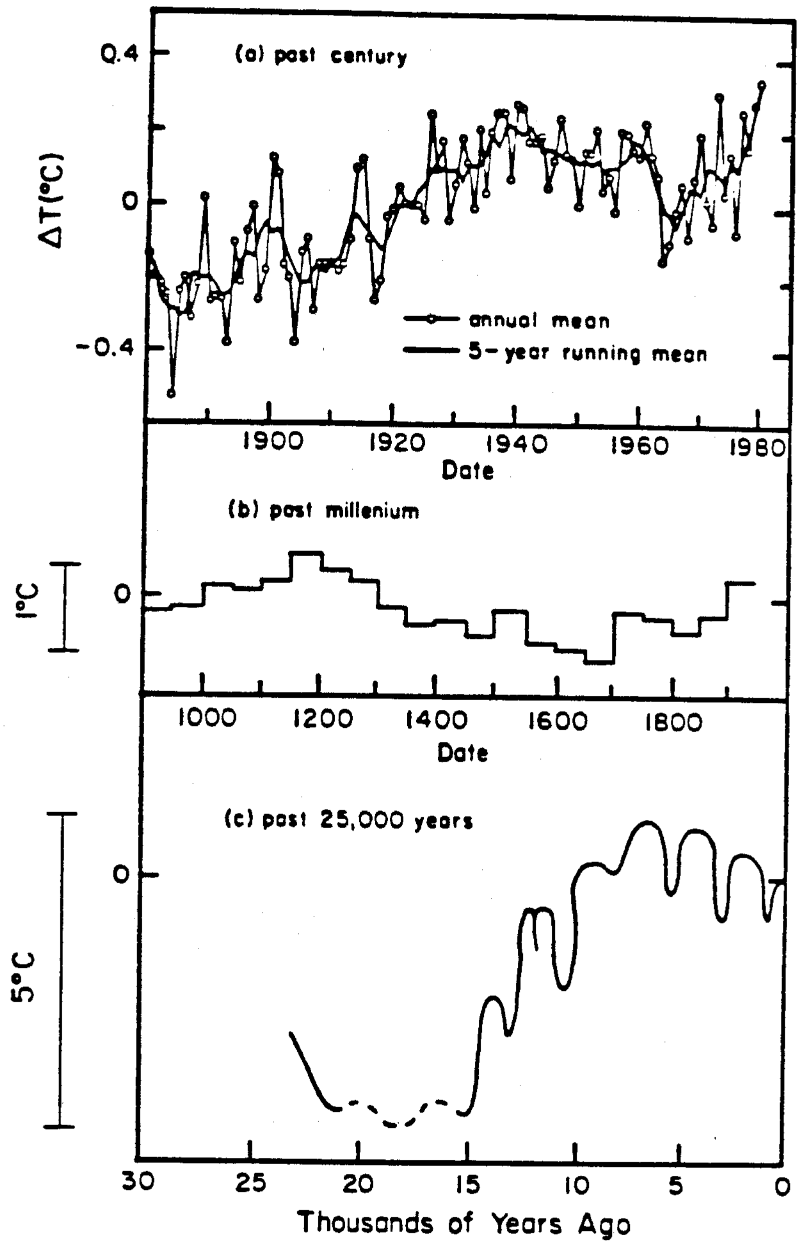


Figure 6. Global temperature trend for the past century (a), millenium (b), and 25,000 years (c). (a) is based on Hansen et al. 1981, updated through 1981. (b) is based on temperatures in central England, the tree limit in the White Mountains of California, and oxygen isotope measurements in the Greenland ice (W. Dansgaard, private communication), with the temperature scale set by the variations in the last 100 years. (c) is based on changes in tree lines, fluctuations of alpine and continental glaciers and shifts in vegetation patterns recorded in pollen spectra (National Academy of Sciences 1975), with the temperature scale set by the 3°-4°C cooling obtained in a 3-D climate model (Hansen et al. 1984) with the boundary conditions for 18,000 years ago. Thus the shapes of curves (b) and (c) are based on only Northern Hemisphere data.

of Sciences 1975). During the peak of the current interglacial (Altithermal period 5,000 to 10,000 years ago) the mean temperature is estimated to have been 0.5°-1.0°C warmer than today (Figure 6).

A comparison of the temperature changes projected for the next few decades with estimated temperatures for the past 150,000 years is shown in Figure 7. By the early twenty-first century the global temperature should have risen well above any level experienced in the past 100,000 years.

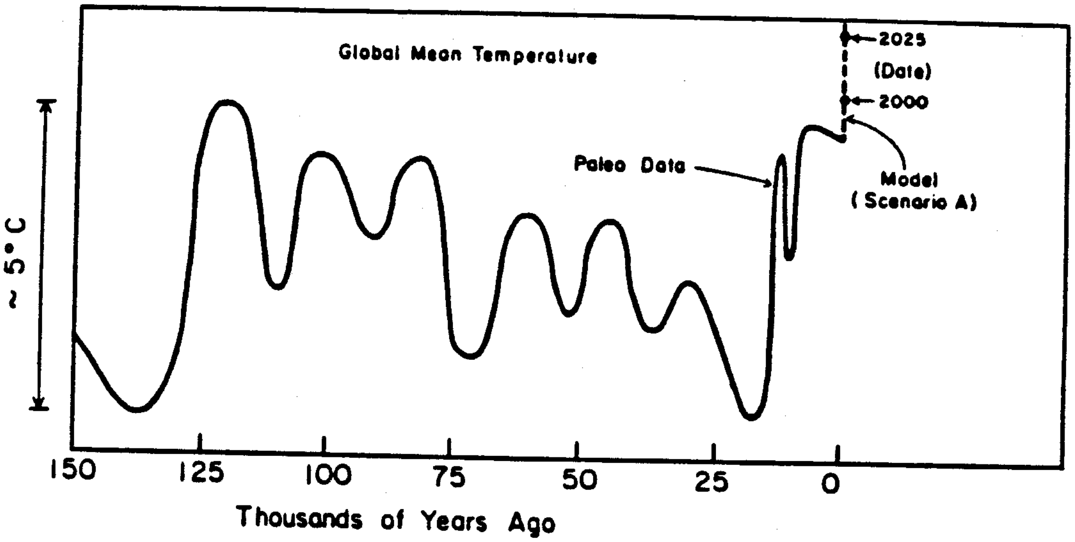


Figure 7. Global temperature trend for the past 150,000 years and as projected for the next few decades on the basis of the global climate model simulation with Scenario A trace gas trends.

TEMPERATURE CHANGES IN THE UNITED STATES

How might temperature changes of the magnitude predicted alter the number of days with temperatures above a given limit for Washington, D.C. and other U.S. cities? We estimate this 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 gridbox that includes that city. This procedure tends to minimize the effects of any errors in the model's control run climatology. Although we should, in principle, also examine the effect of changes in higher moments of the temperature distribution, Mearns et al. (1984) have shown that changes in the higher moments have relatively little effect on the total number of days above a temperature extreme.

We have carried out this procedure for several U.S. cities for the equilibrium change in climate for doubled CO_2. Because of the climate system's finite response time, the results may be most applicable to some time in the middle of the twenty-first century, if the trace gas growth rate of Scenario A is approximately correct.

The results of this exercise for several cities in the United States are shown in Figure 8. The number of days per year in which the maximum daily temperature exceeds 38°C (100°F) increases from about one to twelve in Washington and from three to twenty in Omaha. The number of days with maximum temperature exceeding 32°C (90°F) increases from about thirty-five days to eighty-five days in both cities. The number of days per year in which the nighttime temperature does not fall below 27°C (80°F) increases from less than one day in both cities to nine days in Omaha and nineteen in Washington, D.C. Analogous results for six other U.S. cities are included in Figure 8.

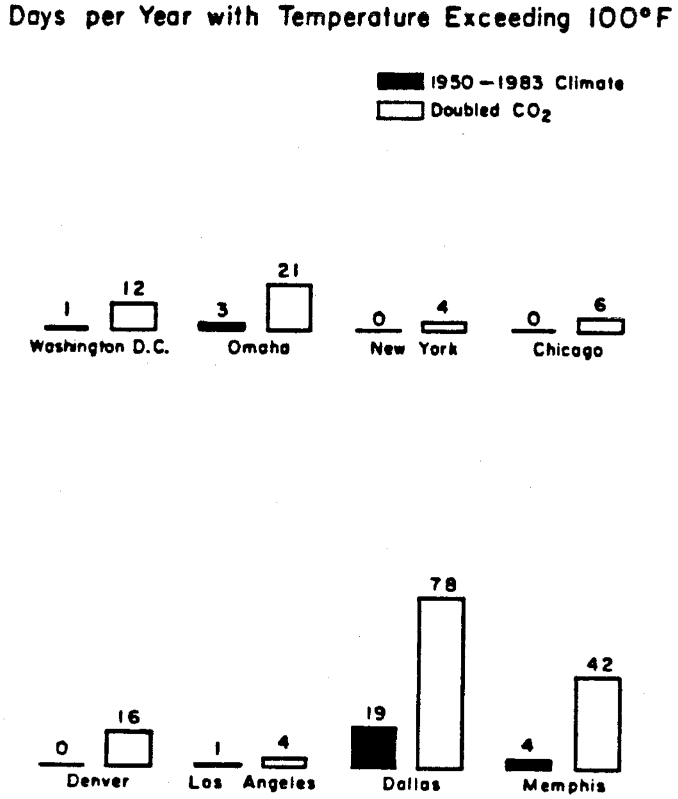
There are a number of reasons why these estimates may differ from the real world response. Principal among these are the following. First, the estimates are based on a model with a sensitivity of 4°C for doubled CO_2; the real world sensitivity is uncertain by about a factor of two. Second, the model assumes that the ocean will continue to operate 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.

A number of expected effects of the greenhouse warming in the United States are summarized in Table 1. The summer cooling requirements in some United States cities will increase several times. On the other hand, heating degree days in the winter decrease on the order of 50 percent. The winter warming, expected to exceed that in summer, may also affect such things as the ability of indigenous forests to survive (Shantz and Hoffman 1986), and the amount, type, and distribution of precipitation. Table 1 also indicates that the growing season will increase in the United States, typically by fifty days, and it is expected that increasing atmospheric CO_2 will enhance plant growth (Lemon 1983). Nevertheless, the high midsummer temperatures could conceivably result in lower agricultural productivity, as occurred in (regional) midsummer heat waves in the United States in 1980 and 1986. Quantitative evaluation of beneficial and detrimental effects will require greatly improved climate forecast capabilities as well as research in societal impact.

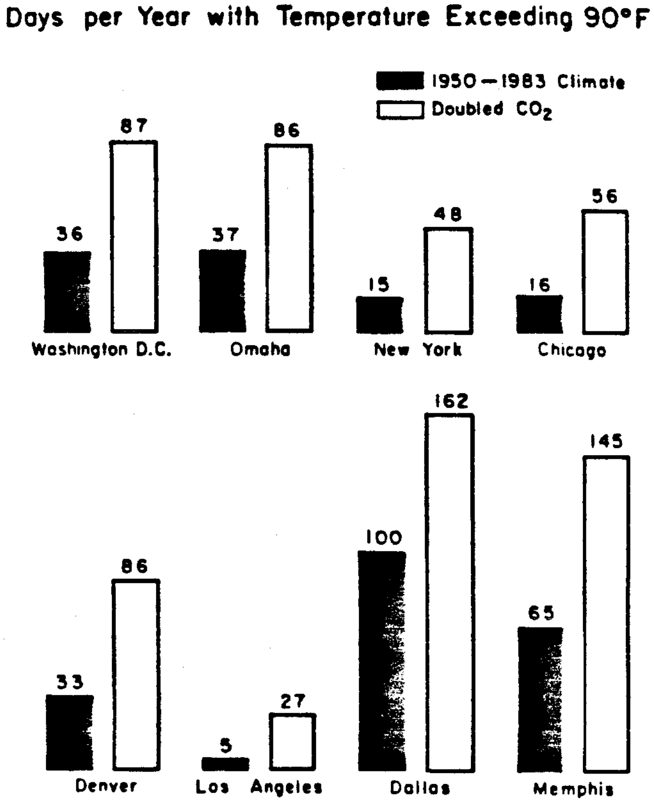
We conclude that the magnitude of temperature changes predicted by current climate models is sufficiently great that, on the average, the warming will be very noticeable to the populations at middle latitudes. Other discussions of the practical impacts of greenhouse warming have focused on possible indirect effects such as changes of sea level, storm frequency, and drought. We believe, however, that the temperature changes themselves will substantially modify the environment and have a major impact on the quality of life in some regions.

EVIDENCE NEEDED TO CONFIRM AND QUANTIFY THE GREENHOUSE THEORY

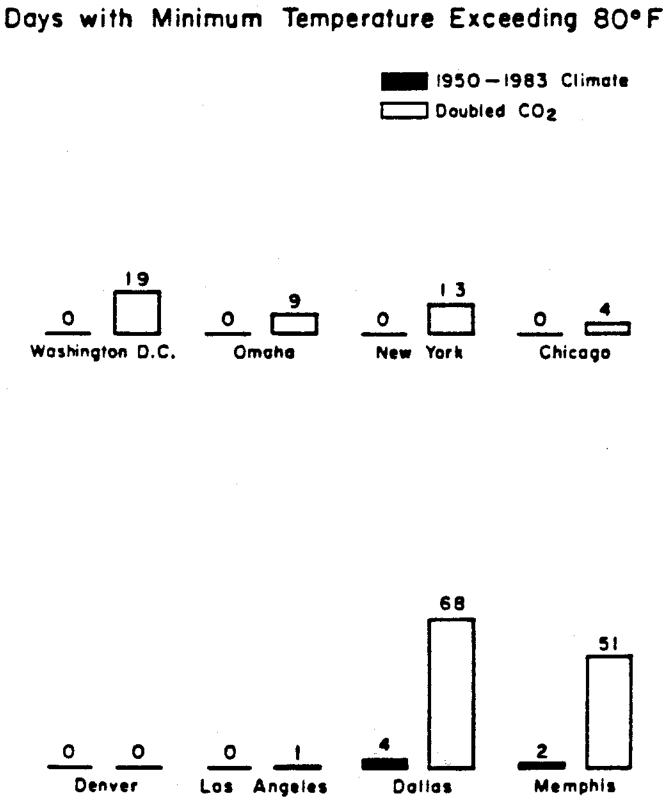
From a scientific point of view, evidence confirming the essence of the greenhouse theory is already overwhelming. However, the greenhouse issue is not likely to receive the full attention it deserves until the global temperature rises above the level of natural climate variability. This will not occur at some sharp point in time, but rather gradually over a period of time. If our model is approximately correct, that time may be soon, within the next decade.



(a)



(b)



(c)

Figure 8. 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 temperatures for 1950-1983.

Table 1.

Table 1. Temperature increases, ΔT, due to doubled CO_2 for representative months; number of days per year in which the daily maximum temperature exceeded 100°F and 90°F, and in which the minimum temperature exceeded 80°F for the 1950-1983 and doubled CO_2 climates; number of cooling degree days (base 80°F), heating degree days (base 65°F) and length of growing season for the 1950-1983 climate and as estimated for doubled CO_2.

City	ΔT (°F)				Days T_{max}>100°F		Days T_{max}>90°F		Days T_{min}>80°F		Cooling Degree-Days		Heating Degree-Days		Growing Season (days)	
	Jan	Apr	July	Oct	Today	$2*CO_2$	Today	$2*CO_2$	Today	$2*CO_2$	Today	$2*CO_2$	Today	$2*CO_2$	Today	$2*CO_2$
Washington	7.9	7.2	6.6	7.1	1	12	36	87	0	19	92	470	4181	2642	233	278
New York	7.9	7.3	6.7	6.3	0	4	15	48	0	13	47	284	4948	3289	236	271
Chicago*	10.0	8.9	5.2	7.6	0	6	16	56	0	4	22	197	6636	4350	178	232
Omaha	10.4	9.0	6.2	8.4	3	21	37	86	0	9	81	396	6284	4041	179	231
Denver	11.7	8.7	6.1	9.9	0	16	33	86	0	0	4	118	6007	3659	162	206
Los Angeles	9.3	9.5	7.5	9.2	1	4	5	27	0	1	8	100	1442	212	365	365
Dallas	7.8	8.4	7.4	8.7	19	78	100	162	4	68	477	1343	2477	1205	253	313
Memphis	8.5	10.0	6.7	8.7	4	42	65	145	2	51	221	991	3249	1531	234	311

* Chicago's record based on 25 years 1959-1983.

When that point in time is reached people will begin to ask practical questions and want quantitative answers. We are now totally unprepared to provide information of the specificity that will be required. Our understanding of the climate system and our ability to model climate must be vastly improved. Some of the tasks, such as the development of a realistic ocean model appropriately interactive with atmospheric climate changes, will require major long-term efforts.

The greatest need, in our opinion, is for global observations of the climate system over a period of at least a decade. 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. Prestigious scientific groups, such as the Earth System Sciences Committee appointed by the NASA Advisory Council, have defined the required observations in detail.

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