The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment

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Since the dawn of the industrial era, the atmospheric concentrations of several radiatively active gases have been increasing as a result of human activities. The radiative heating from this inadvertent experiment has driven the climate system out of equilibrium with the incoming solar energy. According to the greenhouse theory of climate change, the climate system will be restored to equilibrium by a warming of the surface-troposphere system and a cooling of the stratosphere. The predicted changes, during the next few decades, could far exceed natural climate variations in historical times. Hence, the greenhouse theory of climate change has reached the crucial stage of verification. Surface warming as large as that predicted by models would be unprecedented during an interglacial period such as the present. The theory, its scope for verification, and the emerging complexities of the climate feedback mechanisms are discussed.

IN 1827, THE PHYSICIST-MATHEMATICIAN JEAN-BAPTISTE Fourier (*1*, p. 569) stated aptly: "The question of global temperatures, one of the most important and most difficult in all natural philosophy, is composed of rather diverse elements which should be considered under one general viewpoint" (translation from French). A century and a half later, several national and international research groups (*2*) are studying the diverse elements of the climate system. The fundamental motivation for the surge of interest in climate studies is the growing scientific concern that human activities may significantly alter the world's climate, if they have not already done so. The sources for this concern are the observed changes in the atmospheric gaseous composition. Recent advances in the observational area of in situ gas sampling (*3*) have shown that the concentrations of several atmospheric trace gases have increased significantly all over the globe during the last decade (Table 1). Chemical analyses of gases trapped in ice cores reveal that the increase began during the 19th century (Table 1). Model studies of the chemical balance of the atmosphere, the ocean, and the biosphere provide compelling arguments for attributing the observed increases to human activities (*2, 4*).

The gases listed in Table 1 absorb infrared (IR) radiation (also known as terrestrial or thermal radiation) emitted by the relatively warmer surface and emit radiation to space at the colder atmospheric temperatures, leading to a net trapping of IR energy within the atmosphere (the greenhouse effect). The long-term climate is governed by a balance between the absorbed solar radiation and the emitted IR. When there is enhanced IR trapping, for example, as a result of an increase in the concentrations of gases shown in Table 1, excess energy is suddenly available to drive the climate system. The result, according to the theory, is a "vigorous" climate system, that is, a warmer globe with a more active hydrological cycle. The earth warms until the excess IR energy trapped by the greenhouse gases is radiated to space as IR emission. Because of the nonlinear interactions between the atmosphere, the cryosphere (ice and snow), the oceans, and the land, the predicted warming is not uniform but varies significantly with latitude, longitude, altitude, and season. The temperature and pressure gradients that result from the nonuniform warming patterns can alter the general circulation of the atmosphere and the oceans.

The greenhouse effect of the atmosphere was pointed out, perhaps for the first time, by Fourier (*1*), who also suggested that human activity can modify climate. The formal foundation for the greenhouse theory of climate change was laid in 1896 by Arrhenius

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Table 1. Trace gas concentrations and trends: observed and projected. The concentrations are from (*4*); the decadal trends for 1975 to 1985, showing the percentage of increase in concentrations, are from (*3*).

Gas	Concentrations: Pre-1850	Concentrations: 1985	Observed trends for 1975–1985 (%)	Mid-21st century
CO_2	275 ppmv	345 ppmv	4.6	400–600 ppmv
CH_4	0.7 ppmv	1.7 ppmv	11.0	2.1–4 ppmv
N_2O	0.285 ppmv	0.304 ppmv	3.5	0.35–0.45 ppmv
CFC-11	0	0.22 ppbv	103.0	0.7–3.0 ppbv
CFC-12	0	0.38 ppbv	101.0	2.0–4.8 ppbv
Tropospheric O_3* (below 12 km)		10–100 ppbv		
CH_3CCl_3	0	0.13 ppbv	155.0	
CCl_4	0	0.12 ppbv	24.0	

*Values (below 9 km) for before 1850 are 0 to 25% less than present-day; values (below 12 km) for mid-21st century are 15 to 50% higher.

(5), who dealt with the climatic effects of changes in atmospheric CO_2. On the basis of his finding that a doubling of atmospheric CO_2 would warm the globe by 5 K, Arrhenius concluded that past glacial epochs may have occurred largely because of a reduction in atmospheric CO_2. This conclusion is rapidly gaining favor because analyses of air trapped in glacier ice have revealed that CO_2 concentrations in the past fluctuated from about 270 to 300 parts per million by volume (ppmv) during interglacial periods to about 180 ppmv during periods of glacial advance (6). Finally, Callendar (7) concluded in the late 1930s that human activities were causing an increase in atmospheric CO_2, and that this increase could initiate a global warming. In 1967, Manabe and Wetherald (8) provided quantitative results for the CO_2-induced global warming, on the basis of a model that treated the concepts of global energy balance and radiative-convective equilibrium (9). The theory of climate change involving CO_2 variations is now viewed as one of the major mechanisms for understanding climate variations of the past, including the Archean (10), the Cretaceous (10), and the ice ages of the Pleistocene (6).

The importance of the other trace gases was not recognized until the last decade when it was found that the addition of one molecule of CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2) can have the same greenhouse effect as the addition of 10^4 molecules of CO_2 to the present atmosphere (11). The important non-CO_2 trace gases that may govern climate change include CFCs, CH_4, N_2O, ozone (O_3), and more than a dozen synthetic chemicals (12, 13). These developments set the stage for a number of recent theoretical and model studies (2, 4, 12, 13). The conclusions of these studies can be summarized as follows: (i) the observed increases in trace gas concentrations from the mid-19th century to the present have significantly increased the radiative heating of the surface and atmosphere; (ii) there will be a severe reduction of the upper stratosphere O_3 and a cooling of the mid- to upper stratosphere and warming of the surface and troposphere; and (iii) if the observed decadal trace gas growth rate continues unabated, the cumulative surface warming (predicted theoretically) would, in the next two decades, become large enough to manifest itself unambiguously in the global temperature records.

Thus the greenhouse theory of climate change has reached the crucial point of verification because of the inadvertent experiment being performed on the atmosphere by human activities. Revelle and Suess (14) coined the phrase "large-scale geophysical experiment" to describe the anthropogenic increase in the atmospheric CO_2 concentration.

Climate Forcing

The greenhouse effect. The important radiatively active gases in the present atmosphere are H_2O, CO_2, and O_3; their ability to intercept IR radiation has been demonstrated by satellite measurements (Fig. 1) (15). The upper boundary of the shaded region in Fig. 1 is the emission by the ocean surface (radiating at a temperature of 300 K), whereas the lower boundary is the radiation measured at satellite altitudes; the difference is the net energy absorbed or, alternately, trapped within the lower atmosphere. The absorption features of CO_2 between 13 to 17 μm, O_3 between 9 to 10 μm, and H_2O in the entire spectral domain are seen. On a global-annual average basis, the surface emits about 390 W m^{-2}, whereas the radiation emitted to space, as measured by satellites, is only about 237 W m^{-2}. The balance of 153 W m^{-2} is the IR radiation effectively trapped by the atmosphere (including clouds), which should be compared with the absorbed solar radiation of 237 W m^{-2}. Without this greenhouse effect, the surface would cool to about 255 K (13) from its present-day value of 288 K, and the planet would be covered with ice.

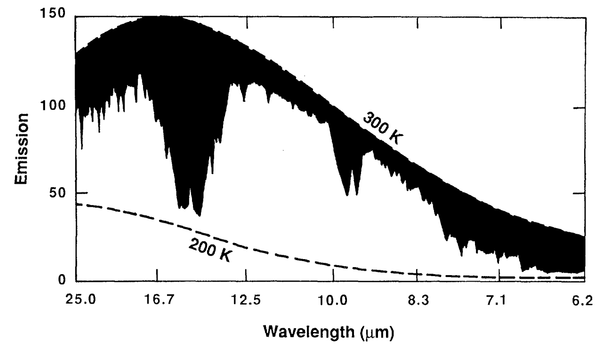


Fig. 1. Sample spectra from the infrared interferometer spectrometer onboard Nimbus 3 satellite. The dashed lines indicate the outgoing long-wave blackbody emission at the temperatures indicated. Emission is measured in arbitrary units. The scene is tropical Pacific Ocean under clear-sky conditions. [Adapted from (15) with permission, copyright by American Geophysical Union, Washington, DC]

The human effect: dirtying the atmospheric window. Nearly 80% of the radiation emitted by the surface in the region from 7 to 13 μm escapes to space (Fig. 1) because the atmosphere, at least the preindustrial atmosphere, is quite transparent in this region. Because of the transparency, this region is referred to as the "window." Outside the window region, most of the surface radiation is absorbed by the atmosphere, and then reemitted to space at the much colder atmospheric temperatures (Fig. 1).

Remarkably, most synthetic gases absorb strongly in the window region (Fig. 2), and this absorption by pollutants has literally the effect of "dirtying" the atmospheric window. The synthetic gases are extremely effective compared with CO_2. The radiative energy (ΔQ) trapped in the surface-atmosphere system is estimated to be (2, 4): ΔQ(CO_2; from 300 to 600 ppmv) ≈ 4 W m^{-2}; and ΔQ(CFC-11 and CFC-12; from 0 to 2 parts per billion by volume) ≈ 1 W m^{-2}. CFCs are so effective because (i) their absorption occurs in the window region; (ii) their absorption band strengths are significantly stronger than that of CO_2 (Fig. 2); and (iii) the concentration of CO_2 is so large (300 ppm) that this gas is optically thick, and hence its greenhouse effect scales logarithmically with the concentration, whereas the greenhouse effect of CFCs scales almost linearly (11, 13).

Climate Response

The response of the climate to an increase in the greenhouse forcing consists of restoring the energy balance at the top of the atmosphere (8, 13). I develop the concepts on the basis of a hypothetical zero-dimensional model, which can be expressed as:

$$H\frac{dT'}{dT} = \Delta Q - R' \quad (1)$$

where H is the heat capacity of the coupled ocean-atmosphere, T' is the surface temperature change, ΔQ is the radiative heating, and R' is the change in the energy leaving the system. If R' is equal to $(dR/dT)T'$ and ΔQ is the heating imposed at time $t = 0$, the equilibrium surface temperature change ΔT_s is the steady-state solution of Eq. 1 given by

$$\Delta T_s = \frac{\Delta Q}{\lambda} \quad (2)$$

where $\lambda = dR/dT$ is the climate feedback parameter.

The Role of Feedbacks: Water Phase Changes

The parameter λ is determined by the feedback processes in the climate system and has been the subject of research during the last two decades. The current estimate for λ is between 0.9 and 3.6 W m^{-2} K^{-1} (*13*). The upper limit for λ is obtained by assuming that the climate system is devoid of all feedbacks other than IR radiative damping and that it emits IR radiation like a blackbody with an equilibrium temperature of 255 K. Modern day three-dimensional general circulation models (GCMs) yield a value between 0.9 to 1.2 W m^{-2} K^{-1}, yielding a ΔT_s (for doubled CO_2) of 3.5 to 4.5 K (*13, 16, 17*). For a doubling of CO_2, that is, $\Delta Q \approx 4$ W m^{-2}, Eq. 2 and the range for λ given above yield an equilibrium surface warming ΔT_s between 1.1 and 4.5 K. The amplification from the case of a blackbody planet is largely due to feedbacks involving H_2O phase changes.

Liquid to vapor: H_2O greenhouse feedback. This feedback results from the exchange of radiative and latent heat fluxes (Fig. 3) between the atmosphere and the ocean-land surface. Figure 3 illustrates model results for the case of a doubling of CO_2 (*18*). Out of the 4 W m^{-2} of CO_2 heating, roughly 25% is deposited at the surface as increased emission from CO_2, and the balance is trapped in the troposphere. Together, the increase in the IR energy warms the troposphere and the ocean (process 2), which starts the feedback loop 3 in Fig. 3. More moisture evaporates from the warmer ocean and land. The latent heat is released as moisture condenses through precipitation. The warmer troposphere, as a result of the latent heat release and the direct greenhouse heating, holds more vapor for the following reasons: observations of the atmospheric humidity profile as a function of latitude and season suggest that the atmosphere tends to conserve its relative humidity with a change in temperature (*8*); as a result, the absolute humidity is determined by the saturation vapor pressure, which increases exponentially with temperature. The enhanced water vapor, in turn, traps more IR radiation and amplifies the greenhouse effect. In one-dimensional climate models, where this feedback can be selectively turned off, the H_2O greenhouse feedback amplifies the air temperature warming by a factor of ≈ 1.5 (*17, 18*) and the surface warming by a factor of ≈ 3 [table 4 in (*18*)].

Solid to liquid and vapor: Ice-albedo feedback. Another well-studied effect is the ice-snow albedo feedback. The greenhouse warming melts the sea ice and snow cover. The underlying surface, be it ocean or land, is much darker than the ice or snow, such that it absorbs more solar radiation, thus amplifying the initial warming. For example, sea ice with overlying snow reflects about 40 to 60% of the solar radiation, whereas the open ocean at high latitudes reflects only 20 to 30%. Melting the sea ice during spring and summer can increase the polar ocean absorption of solar radiation by as much as 50 to 100 W m^{-2}, which should be compared with the direct CO_2 radiative heating of about 4 W m^{-2}. The ice-albedo feedback amplifies the global warming by only 10 to 20% (*17, 19*); but locally, near the sea-ice margins and in polar oceans, the warming can be larger than the global warming by factors ranging from 2 to 4.

Vapor to liquid and solid: Cloud feedback. The increased moisture from the warmer oceans should alter cloud distributions and characteristics. The nature of these cloud changes and how these changes will affect the radiative heating is unclear (*20, 21*). The difficulty is the lack of a theory that can relate cloud scale processes to planetary scale features of clouds. As a result, cloud feedback is one of the largest sources of uncertainty in the theory of climate change. Next to water vapor, clouds play the most dominant role in governing the radiation energy balance of the climate system. For example, the reflectivity of clouds increases the albedo (reflectivity) of the planet from about 10% (the clear sky albedo) to the observed value of 30% (*20*). An increase in the planetary albedo of just 0.5% is sufficient to halve the greenhouse effect of CO_2 doubling. Clouds are also extremely efficient in trapping IR. The tropical cirrus clouds trap as much as 100 to 200 W m^{-2}, and global average values, although not known reliably yet, may be between 25 and 50 W m^{-2} (*20*). Recent GCM studies have indicated that the magnitude of the problem has increased significantly. The GCM sensitivity to CO_2 doubling increased from roughly 2 to 3 K for the models developed in the 1970s to about 4 to 5 K for current models (*16, 17*). One of the major factors that contributed to the increased sensitivity is the inclusion of interactive clouds. However, since clouds are treated primitively in GCMs, it is premature to make reliable inferences from GCM studies.

Ocean-atmosphere interactions. The oceans influence the climate response in two fundamentally important ways. First, because of the importance of the H_2O greenhouse feedback, the response of the tropospheric temperatures and even the land surface temperatures would be governed by the warming of the ocean surface. If for some reason the ocean does not respond to the greenhouse heating, the H_2O feedback would be turned off since increased evaporation from the warmer ocean is the primary source for increasing atmospheric H_2O. Second, oceans can sequester the radiative heating into the deeper layers, which, because of their enormous heat capacity, can significantly delay the warming (*21–23*).

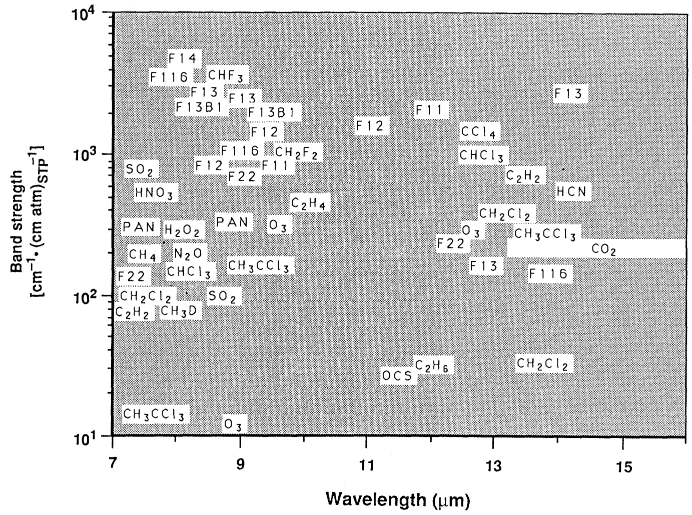


Fig. 2. Spectral locations of the absorption features of various trace gases. The spectral region between 7 and 13 μm is referred to as the atmospheric "window." Abbreviations: F, Freons; PAN, peroxyacetyl nitrate; and STP, standard temperature and pressure. [Adapted from (*13*) with permission, copyright by American Geophysical Union, Washington, DC]

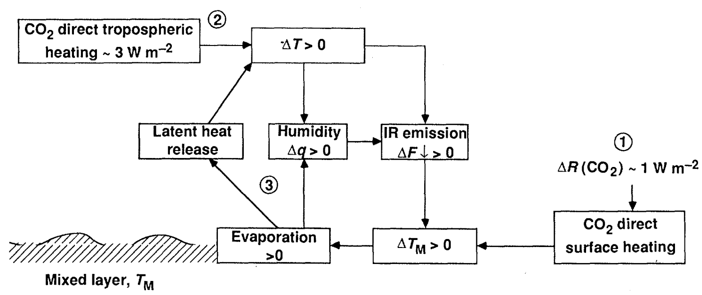


Fig. 3. Schematic of the H_2O feedback involving ocean-atmosphere thermal interactions. This is the dominant mechanism by which the greenhouse feedback warms the surface. Abbreviations: T, troposphere temperature; T_M, mixed layer temperature; $F\downarrow$, downward infrared emission; q, specific humidity; and R, the radiative (IR plus solar) flux change at the surface due only to change in CO_2. Values correspond to doubling of CO_2. Numbers within circles designate the feedback loops.

Table 2. Estimated increase in the radiative forcing. The value for the global average absorbed solar radiation is 237 W m^{-2}. The uncertainties in the estimates are about ±30%.

Gas	Radiative forcing (W m^{-2})	
	1850–1985 (*4*)	1975–1985 (*13*)
CO_2 only	1.3	0.24
All trace gases	2.2	0.45

Chemical Interactions and Ozone Changes

Stratospheric O_3. There are no known important sinks for CFCs in the troposphere (*24*). They are ultimately broken down in the stratosphere above 25 km by photolysis, which frees the highly reactive chlorine. As a result, their tropospheric lifetimes are long: about 65 years for $CFCl_3$ and 110 years for CF_2Cl_2. The chlorine competes with nitrogen oxides for odd oxygen species including O_3, and the result is an efficient catalytic destruction of O_3 by chlorine until it is removed from the system as HCl. Atmospheric chemistry models predict that, at present rates of emission of CFCs, severe O_3 reduction ranging from 15% near 30 km to about 40% near 45 km (*24*) will result. The stratosphere derives its name because of the increase in temperature with altitude, that is, a stably stratified region. This thermal inversion is maintained by O_3 solar heating, and hence O_3 destruction would cool the stratosphere. For example, a 50% reduction in O_3 would cool the upper stratosphere by as much as 20 K (*13*). Furthermore, O_3 modulates the solar and IR flux incident on the troposphere. A reduction in stratospheric O_3 would allow more sunlight to reach the surface and tend to warm it. This warming will be offset by reduced IR fluxes emitted by the cooler stratosphere and also by a reduced O_3 greenhouse effect. The net effect, that is, surface warming or cooling, critically depends on the vertical distribution of the O_3 change (*8, 13*).

Tropospheric O_3. The 9.6-μm band of O_3 is an important source of IR opacity for the troposphere (*25, 26*). Photolysis of O_3 in the troposphere produces $O(^1D)$, which, in turn, reacts with H_2O to release hydroxyl (OH) radicals through $H_2O + O \rightarrow 2OH$. The highly reactive OH is the primary sink for many tropospheric gases and pollutants including O_3, CH_4, CO, and NO (*25*). Hence, increases in CH_4, such as those during the last century, could have caused a substantial (20 to 40%) reduction in OH (*25*), which in turn, could cause an increase in tropospheric O_3 by as much as 20% (*25, 26*). Since CH_4 oxidation leads to the formation of H_2O, an increase in CH_4, an important greenhouse gas, can lead to an increase in H_2O in the stratosphere. Likewise, an increase in the CO concentration can tie up more OH in the oxidation of CO. Thus, through chemical reactions, an increase in either a radiatively active gas such as CH_4 or even a radiatively inactive gas such as CO can increase the concentrations of several important greenhouse gases (*25*).

Model Predictions

Radiative forcing. The estimated radiative forcing due to the observed trace gas increases is shown in Table 2. Human activities during the last century have enhanced the radiative heating of the planet by an amount (2.2 W m^{-2}) comparable to increasing the sun's output by about 0.9%. During the 1975 to 1985 decade, about 0.45 W m^{-2} was added to the system, and the non-CO_2 gases contributed ≈50% to the total heating.

Equilibrium surface warming. If the planet had no thermal inertia, the trace gas increase would be simultaneously accompanied by the surface warming given by Eq. 2, such that, in Eq. 1, the R' term balances ΔQ at each instant in time. Hence the ΔT_s given by Eq. 2 is referred to as the equilibrium surface warming. For the radiative forcing shown in Table 2, Eq. 2 in conjunction with the range of λ mentioned earlier yields

$$0.6 \leq \Delta T_s(1850 \text{ to } 1985) \leq 2.4 \text{ K} \qquad (3)$$

The inferred trace gas increases from the preindustrial era to the present have committed the planet to an equilibrium surface warming of about 0.6 to 2.4 K. Furthermore, at the current rate of increase in the trace gases, the committed equilibrium warming of the globe increases by about 0.13 to 0.5 K per decade. If the current rate of trace gas increase continues unabated, the equilibrium warming can double to 1.2 to 5 K in another 50 years (*4*).

Transient effects. Because of its large thermal inertia, the ocean will sequester some of the radiative heating and hence the transient warming will lag behind the equilibrium warming. Since the trace gases are increasing with time, the lag will increase with time. The important consequence of this transience is that the climate system is increasingly in a state of disequilibrium with the radiative forcing (*17*). The lag, which is currently thought to be in the range of a few decades to a century (*13, 17, 23*), depends on ocean circulation, vertical mixing in the oceans, and the climate feedback parameter (*23*). Data on these three quantities are not adequate. However, the main effect of the ocean in delaying the greenhouse warming can be conceptualized with a simple "box diffusion" model (*22*). This model asserts that heat perturbations are mixed as a passive tracer into the deeper oceans in a manner that can be modeled by one-dimensional diffusion. The vertical penetration of heat anomalies within the oceans, as predicted by the box diffusion models, provides a good fit to the global averaged results of a coupled ocean-atmosphere GCM (*22*). The values of the diffusion coefficient, k, that yield good agreement with measurements of passive tracers are between 1 to 2 cm^2 sec^{-1}. Analytical studies of these conceptual models suggest (*23*) that for a heating pulse switched on abruptly, the lag behaves as k/λ^n where $1 \leq n \leq 2$ (*23*). For the realistic case of a heating perturbation that is growing with time, the concept of a thermal lag is not very useful. A more useful parameter is β, which is the ratio of the transient temperature change to the equilibrium warming. For the observed trace gas changes of the past century, β varies from ≈0.45 for λ = 0.9 W m^{-2} K^{-1} to ≈0.75 for λ = 3.6 W m^{-2} K^{-1} (*13, 23*). If we apply these values of β to Eq. 3, the expected trace gas warming from 1850 to 1985 is estimated to be between 0.5 and 1.1 K. Because of the inverse relation between the lag and λ, the fourfold range in the equilibrium warming has severely been reduced in the transient case.

Other changes. The following effects are largely derived from GCM studies of the CO_2 doubling problem (*2*): (i) the warmer globe will be more humid and wetter; and (ii) the warming will be amplified in the polar regions by factors of 1.5 to 3 (*2, 16, 17*). The threefold amplification occurs mainly during the winter season over the margins of sea ice between 50° and 70° latitude. The warming in the high-latitude continents peaks during spring and is larger by roughly a factor of 1.5 than the global average warming (*16, 17*). Other postulated effects include summer drying in mid-latitudes and a rise in sea level (*2*). The degree of uncertainty in the computed regional changes is significantly larger than the global average estimates (*2*).

Stratospheric cooling. The computed surface warming is accompanied by a significant cooling of the mid- to upper stratosphere, that is, at altitudes above 30 km (*4, 13, 14*). The cooling is partly due to increased IR emission from the CO_2-rich stratosphere and due to the reduced solar heating from the O_3 reduction that is predicted to

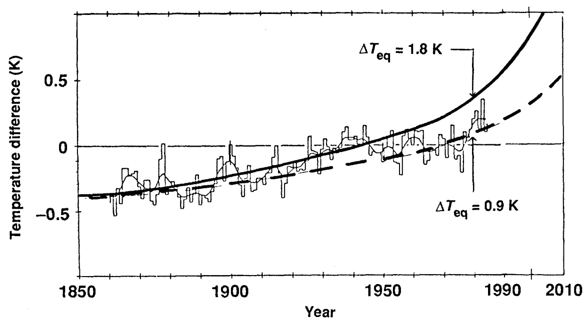


Fig. 4. Comparison of observed (*28*) and computed (*13*) global annual-averaged surface temperature anomalies. The computed anomalies are based on calculations of Lacis and Hansen [as reported in (*13*)] who used a one-dimensional box-diffusion ocean-atmosphere model. The equation for the solid line is λ (see Eq. 2) = 1 W m^{-2} K^{-1}; k (diffusion coefficient) = 1 cm^2 sec^{-1}; current growth rates for trace gas increase beyond 1985; the equilibrium warming for 1850 to 2030 is 5.4 K. The equation for the dotted line is λ = 2 W m^{-2} K^{-1}; k = 2 cm^2 sec^{-1}; reduced growth rates [details in (*13*)]; the 1850 to 2030 equilibrium warming is 2 K. [Adapted from (*13*) with permission, copyright by American Geophysical Union, Washington, DC]

result from the CFC increase. For the period 1860 to 1985, the combined computed effect of CO_2 increase and the CFC increase is as follows: −1 K at 25 km; −2.5 K at 30 km; and a maximum cooling of about 6 K between 45 to 50 km.

The Evidence for Change

The control climate. A control climate needs to be established against which the changing climate can be compared. For example, the climate of the last 12,000 years is significantly different from that of the previous 12,000 years when there was the Great Ice Age; the climate of the last 200 years was different from that of the previous 200 years, which were subject to the Little Ice Age; and the climate of the last 50 years was also much warmer than that of the previous 50 years, when Alpine glaciers were at their southernmost extent. Against such a background of changing climate, the definition of a control climate is not clear, as pointed out by Lorenz (*27*).

Whether the past changes are simply the result of aperiodic behavior of a nonlinear system (*27*) or the result of changes in the climate forcing terms has not been settled yet. However, it should be remembered that summer is always warmer than winter in most latitudes and the tropical regions are always warmer than the poles. These seasonal and latitudinal climate changes are related to the solar forcing. Thus, the following question is raised: Is the human effect large enough to overwhelm the background changes, whatever these may be?

Surface warming. Widespread instrumental records of hemispherical scale surface temperature were begun only in the 1850s; therefore, calibrated records of the climate system before this time do not exist. The spatial sampling is poor before 1900, hence there is a considerable discrepancy in even the sign of the changes between the 1850s and 1900 (*28, 29*). Until a few years ago, the estimates of the global average temperature were largely based on records from land and island stations. The compilation of ocean temperature measurements made on ships was undertaken only recently. A reconstruction of global average temperature (*28*), which includes land and marine temperatures, along with computed temperatures is given in Fig. 4. The observed records reveal a global warming of about 0.5 K from 1850 to 1985; however, the temporal history of the warming and the trace gas increases have varied. For example, the global warming that began in the early 20th century was interrupted during the period 1940 to 1970, when there was a substantial increase in the trace gas forcing.

The observed variations can be described with phase diagrams of just the hemispherical station-averaged temperatures (Fig. 5). The variations are smoothed first by taking time averages of 3 or 5 years (*30*). One 3- or 5-year average (x-axis) is plotted against the following 3- or 5-year average (y-axis). In such a diagram, a linear trend will show as a diagonal line; periodic variation as a circle or closed loop; and aperiodic variations will be intersecting contours. For both hemispheres, the late-19th-century points fall in the southwest quadrant, whereas the late-20th-century points fall in the northeast quadrant, which confirms the existence of an overall warming trend (*28, 31*). However, most of the warming in the Northern Hemisphere takes place abruptly over a 10- to 15-year period (seen in the 5-year average in Fig. 5B), whereas it takes place in a series of "staircase" patterns in the Southern Hemisphere, that is, a warming in one 3- to 5-year period followed by another period of almost no change. Similarly, the substantial warming in the 1970s and early 1980s happened mostly in one 3- to 5-year period in both the hemispheres. The abrupt nature of the climate change, recognized also by earlier studies (*29*), may be a feature of climate changes on the 1,000- to 10,000-year time scales (*32*).

Polar amplification. Observed trends have generally revealed that the global temperature changes are accompanied by significantly larger changes in the polar regions (*20, 31*). This result, by itself, does not verify trace gas effects but does add credence to the polar amplification theory.

Stratospheric cooling. Two studies (*33, 34*) dealing with radiosonde data have shown that the lower stratosphere has cooled since 1965 when global coverage by radiosondes began. Angell's analyses (*33*) show the following global trends for the period 1965 to 1980: −0.14 K per decade for 16 to 20 km and −0.33 K per decade for 16 to 24 km, whereas Labitzke *et al.* (*34*) found −0.24 K per decade at 30 mbar (≈24 km). These decreases should be compared with the computed trace gas cooling trend of about 0.3 K per decade at 30 mbar (*34*). However, it is premature to consider this agreement in trends as verification because of the limited duration of the data.

Other Competing Forcings

Various other radiative forcing terms can influence decadal scale climate changes (*17, 21*); two of them are described here.

Solar irradiance. Accurate measurements of the solar irradiance reveal that the solar irradiance has decreased by 0.1% between 1979 to 1984, which translates into a decrease in the radiative heating of about 0.25 W m^{-2} (*35*). These measurements support the suggestions (*36*) that link climate changes to variations in solar irradiance.

Volcanoes. After the eruption of Laki in Iceland in 1783, Benjamin Franklin suggested that volcanic aerosol clouds in the upper atmosphere scatter sunlight and reduce the solar radiation reaching the surface. Since then, there has been speculation about the surface cooling due to volcanoes. Modern-day measurements have helped resolve some of the controversy surrounding the hypothesis. For example, it is known that volcanoes can eject aerosol precursor gases into the stratosphere; these gases spread globally over a period of several months and are converted to sulfuric acid droplets in the stratosphere (*37*).

The sulfuric acid droplets absorb the longwave radiation emitted by the warmer surface and cause a local heating of the stratosphere. The heating is particularly large within the tropical lower stratosphere because of the warm tropical surface, which enhances the IR radiation intensity, and the very cold lower stratosphere, which minimizes emission of IR radiation by the aerosols. The temperature warming due to this heating will reach a maximum in the lower stratosphere because of its long radiative response time (50 to 100 days). Thus, a heating of only 0.05 K day^{-1} will cause a warming of 3 to 5 K in the lower stratosphere, as was observed in the tropics after the El Chichón eruption in April 1982 (*38*). This confirmation is perhaps the only aspect of the entire climate theory for which there is unambiguous verification.

After the El Chichón eruption in April 1982, the stratospheric visible optical depth in tropical to mid-latitude regions maintained peak seasonally averaged values of about 0.1 to 0.2 for nearly 6 months (*37*) and took about 2 to 3 years to decay to the background values that are less than 0.005. A stratospheric cloud with an optical depth of 0.1 can reflect back to space as much as 3.5 W m^{-2} (*39*). A major eruption, such as El Chichón, with an initial optical depth of 0.1 decaying in 3 years, could contribute as much as 0.2 to 0.4 W m^{-2} to decadal average radiative cooling, which should be compared with the 0.45 W m^{-2} trace gas heating for 1975 to 1985 (Table 2). Although the radiative effects of volcanic aerosols are understood, the surface cooling effect of volcanoes has not yet been satisfactorily demonstrated (*40, 41*).

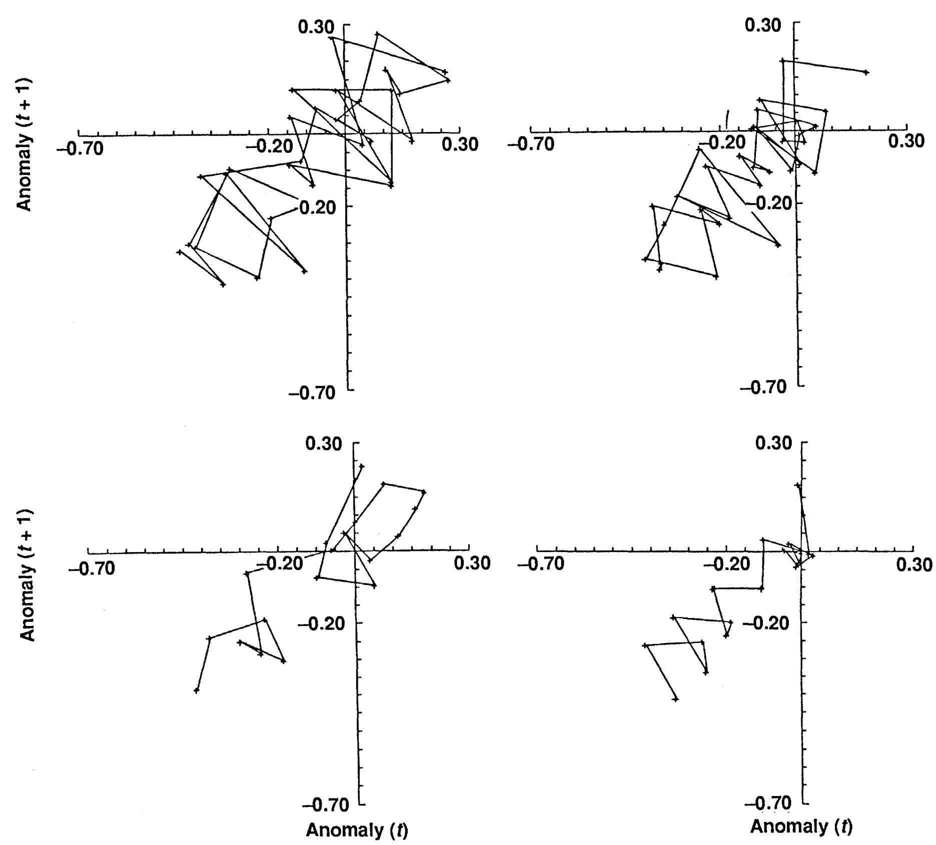
Summary and Discussion

The fundamental effect of the time-dependent trace gas radiative heating is to push the climate system into a state of disequilibrium with the incoming and outgoing energy fluxes. The theory states that the earth tries to restore the equilibrium by warming and by emitting the excess energy to space; about 0.5 to 1 K of this warming should have already occurred. Observed records do reveal a warming of the order of about 0.5 K, but the temporal history of the warming is unlike the pattern anticipated by the theory. The warming occurred abruptly and in bursts. Either the observed warming is not related to the increase in the trace gases or current theories and models of ocean-atmosphere interactions are inadequate to capture the transient response of the climate system to a time-dependent variation in external forcing. The theoretical understanding of the climate system is by no means complete. Some issues that need to be resolved follow.

Climate extremes. If the trace gases continue to increase, the warming, according to the sensitivity of GCMs, can reach 5 K during the next century. A warming of this magnitude would be unprecedented because the present climate is just coming out of the peak of an interglacial period. A warming of 5 K above this peak would likely be beyond the range of validity of current models, particularly with respect to the response of the world's ice sheets and changes in the ocean circulation. On the other extreme, the Vostok ice store (Antarctica) data (*6*) reveal that CO_2 has decreased from about 280 ppm during interglacial to about 190 ppm during glacial time. Furthermore, it has been suggested that the CO_2 variations themselves may help explain the glacial-interglacial cycles (*6*). The radiative cooling due to a CO_2 decrease from 280 to 190 ppm is only 2.5 W m^{-2}; for this cooling to institute a major ice age requires a climate sensitivity even larger than those of current GCMs (*6*).

Cloud microphysics. Recent studies (*42–45*) have made compelling arguments to link cloud microphysics with climate change. The cloud visible optical depth, τ, can be written as $\tau = CL/r$, where C is a constant, L is the cloud liquid water content, and r is the droplet radius. The above relation follows from the fact that r is large enough ($\approx$10 μm) that the scattering can be approximated by geometrical optics, that is, independent of wavelength or radius. The liquid water content $L = (4/3)\pi r^3 N$, where N, the number of cloud droplets, is closely correlated with condensation nuclei. Hence, on combining the above relation for L and τ, one has

$$\tau = cL^{2/3}N^{1/3} \tag{4}$$



Northern Hemisphere: 1885–1984

Southern Hemisphere: 1885–1984

Fig. 5. Phase-plane diagram of observed surface air temperature anomalies. The data are deviations of the hemispherical mean temperatures from the 1959 to 1984 average. Only land stations are included in the hemispherical average. The figure plots 3-year (**top**) and 5-year (**bottom**) averages (x-axis) against the following 3- and 5-year averages (y-axis). The starting period is on the lower southwest quadrant of each diagram, since the early 19th century was a cold period. The initial year is 1885, since the data have severe sampling problems before this period.

where c is a constant. The increase in absolute humidity with T_s could lead to an increase in L (*42*). The resulting increase in τ (Eq. 4) will enhance cloud reflection of solar radiation and provide a negative feedback (*42*). Another mechanism of negative feedback (*43*) suggests that human activities have also increased tropospheric particulates, and this will lead to an increase in N. A variant of this feedback, which involves biogenic processes, has been proposed by Charlson *et al.* (*44*). They pointed out that the value of N over the oceans is predominantly sulfuric acid droplets derived from emission of dimethyl sulfide by marine organisms. They suggested that an increase in T_s may cause an increase in emission of dimethyl sulfide and hence N. These suggestions received indirect support from a recent satellite study (*45*), in which ship tracks that had been spotted amidst marine stratocumulus clouds were consistently brighter in visible wavelengths. This brightness was not due to particulates from the ship smoke (these would be darker) but was due to enhanced cloud condensation nuclei, from the sulfur in the smoke, which enhances cloud visible optical depth according to Eq. 4.

Influence of CH_4, H_2O, and stratospheric clouds. The increase in CH_4 of nearly a factor of 2, along with the various ways it can influence the atmosphere, makes it one of the most intriguing greenhouse gases. An increase in CH_4, because of its coupling with OH, can cause an increase in tropospheric O_3. Also, CH_4, which is oxidized to H_2O in the atmosphere, is an important source for stratospheric H_2O (*13, 17*). In principle, CH_4 can be oxidized to two H_2O molecules. The observed increase in CH_4 from 0.7 to 1.7 ppmv (*4*) can lead to a maximum increase in H_2O of 2 ppmv. The observed H_2O concentration in the stratosphere increases from about 2 to 5 ppmv near the tropical tropopause (10 to 16 km) to about 5 to 8 ppmv above 30 km (*46*). Most of this increase could be due to an increase in CH_4 from the preindustrial to the present time. Stratospheric H_2O enhances the greenhouse effect substantially; a doubling of stratospheric H_2O (entire column) from 5 ppmv can have nearly the same warming effect (*8, 12*) as that due to the observed CO_2 increase during the last century. Because H_2O and other gases are also transported poleward and downward in the stratosphere (*47*), H_2O produced in the tropical middle and upper stratosphere by CH_4 oxidation can be transported to the polar lower stratosphere. This H_2O may contribute to the recently discovered polar stratospheric clouds (*37*) in two ways. First, H_2O may provide the required source for the liquid and solid H_2O in the clouds (*48*). Second, the local radiative cooling from the increased H_2O (*49*) may provide the temperature drop needed for cloud formation. Since the radiative response time of the lower stratosphere is of the order of 50 to 100 days, an increase in the cooling rate of 0.02 to 0.05 K day^{-1} may cool the region by 2 to 3 K (*49*). This cooling is sufficient for H_2O, even at 5 ppmv, to condense in the Antarctic lower stratosphere during winter. Thus climate effects of CH_4 may involve complex interactions among atmospheric chemistry, radiation, thermodynamics, and dynamics.

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