How Sensitive Is the World's Climate?

JAMES HANSEN, ANDREW LACIS, RETO RUEDY, MAKIKO SATO, AND HELENE WILSON

We estimate climate sensitivity from observed climate change on time scales ranging from the 100 000-year periods of major ice ages to brief periods of cooling after major volcanic eruptions. The real-world data indicate that climate is very sensitive, equivalent to a warming of 3 ± 1°C for doubled atmospheric CO_2. Observed global warming of ~0.5°C in the past 140 years is consistent with anthropogenic greenhouse gases being the dominant climate-forcing in that period. But interpretation of current climate change is extraordinarily complex, because of lack of observations of several climate forcings as well as an unpredictable chaotic aspect of climate change. Climate change during the next decade may help confirm knowledge of climate sensitivity, if global climate forcings are accurately observed.

MAJOR CLIMATE CHANGES HAVE BEEN predicted for the 21st century, if anthropogenic heat-trapping (greenhouse) gases continue to increase rapidly. These predictions are based in part on climate models, which are mathematical representations of the complex dynamics of the Earth's climate system. The realism with which models simulate climate is limited by our poor understanding of many climate processes. Thus, if we based predictions of future climate on climate models alone, their significance would be similarly limited.

But climate models are mainly a tool that helps extract information from real-world climate changes. The principal climate characteristic to be evaluated is the global climate sensitivity to a perturbing forcing, such as a change of atmospheric composition. Our most precise knowledge of climate sensitivity comes from data on ancient and recent climate changes.

Climate Forcings, Feedbacks, and Sensitivity

Climate is always changing. Climate would fluctuate without any change of climate forcings. The chaotic aspect of climate is an innate characteristic of the coupled fundamental equations describing climate system dynamics.[12] Chaotic climate change complicates interpretation of observations, but does not diminish the importance of changes of mean climate resulting from external forcing.

A climate forcing is a change imposed on the planetary energy balance that alters global temperature. Examples are change of solar radiation incident on Earth or change of atmospheric CO_2 abundance. A climate forcing is measured by the change in the heating rate of the Earth in watts per square meter (W/m^2). For example, the increases of greenhouse gases CO_2, CFC, CH_4, and N_2O that have occurred since the Industrial Revolution began cause a heating of 2 W/m^2 by decreasing infrared radiation emitted to space.[13]

Climate sensitivity refers to the mean change of climate conditions that occur in response to a specified forcing of global climate. Although many climate parameters—temperature, precipitation, and winds, for example—change in response to climate forcing, the common measure of climate sensitivity is the change of global mean temperature, and the standard forcing is doubling of atmospheric CO_2.

The Earth (Figure 1) absorbs ~240 W/m^2 of solar energy, which heats the planet so that it radiates, on average, that amount of thermal energy

CO_2 = carbon dioxide
CFC = chlorofluorocarbons
CH_4 = methane
O_3 = ozone
N_2O = nitrous oxide
SO_2 = sulfur dioxide

Figure 1.
Western hemisphere.
EARTH SATELLITE CORP

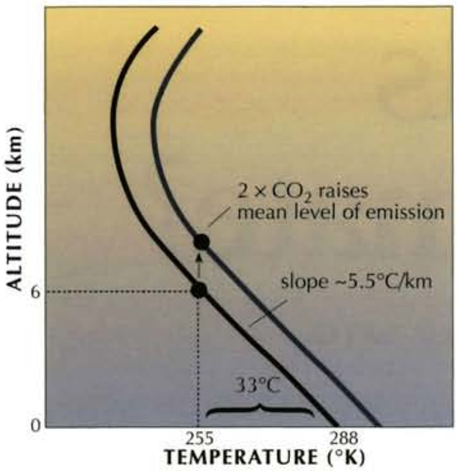

Figure 2.
Greenhouse effect.: Doubled CO_2 increases atmospheric infrared opacity, thus raising by just over 200 m the mean level from which thermal energy escapes to space. Because it is colder at altitude, the energy emitted to space is temporarily reduced and the planet radiates less energy than it absorbs. The temperature must rise by 1.2°C to restore energy balance, if the temperature gradient and other factors are fixed.

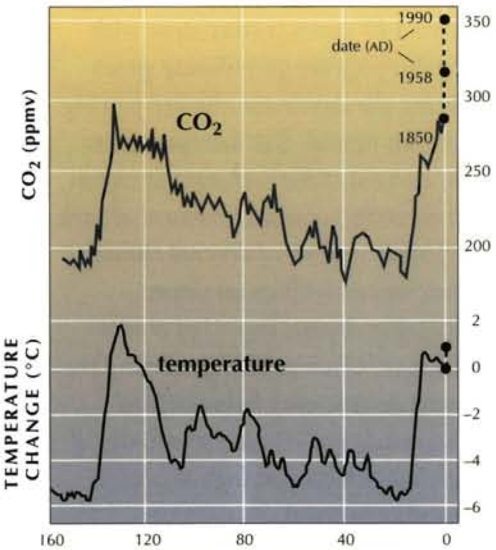

Figure 3.
CO_2 and temperature records from Antarctic ice cores[27] over the past 160 000 years, and recent atmospheric measurements.

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back to space. The effective radiating temperature required to yield this outgoing flux is 255 K (–18°C), which is the temperature at the mean level of emission to space at ~6 km altitude (Figure 2). The mean tropospheric temperature gradient, dependent mainly on atmospheric composition, is ~5.5°C/km. Thus the mean surface temperature is 33°C warmer than it would be if the atmosphere were transparent. This 33°C surface warming is the present greenhouse effect on Earth.

If the amount of CO_2 in the air increases, the atmosphere becomes more opaque, temporarily reducing thermal emission to space. If atmospheric CO_2 is doubled, and all other factors are fixed, the surface must warm 1.2°C to restore energy balance with space (Figure 2). This 1.2°C warming is the "doubled CO_2" greenhouse effect without feedbacks.

Of course other factors are not all fixed. Climate feedbacks are internal reactions of the climate system to (natural or anthropogenic) climate change. Positive feedbacks amplify the climate change; negative feedbacks diminish it. A negative feedback cannot reverse the sense of a climate change, because the feedback is driven by the climate change. But if a feedback were strong enough, it could reduce the climate change to negligible proportions.

Global climate models provide a tool to study climate feedbacks. The models indicate that the air would hold more water vapor in a warmer climate. Because water vapor is a greenhouse gas, this is a positive feedback. Climate models also show that a warmer world would have less area covered by ice and snow, thus increasing absorption of sunlight, again a positive feedback. The models suggest that clouds are a potentially important feedback, but cloud modeling is so primitive that even the sign of this feedback is uncertain.

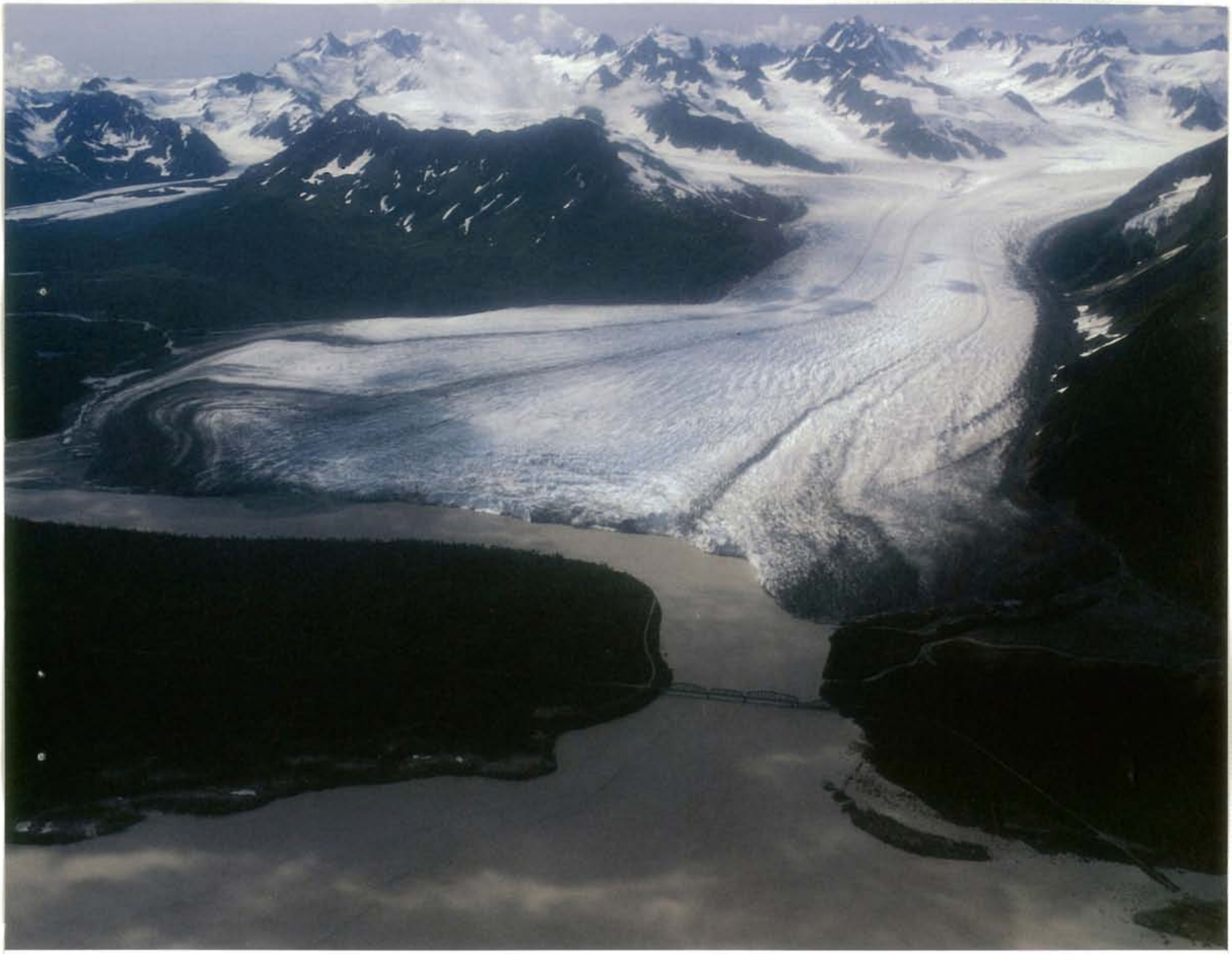
Climate models including these feedbacks yield an equilibrium ($t \rightarrow \infty$) global climate sensitivity between 2 and 5°C for doubled CO_2. This wide range is a result mainly of differences in cloud simulations.[4] Future observations and modeling of climate processes may narrow the range of calculated climate sensitivities. But there may be other significant feedbacks not included in present climate models. So the models alone leave great uncertainty about climate sensitivity.

More precise information on climate sensitivity comes from observations of past climate change. The empirical cases include all feedbacks of the real climate system. To avoid complications of the time-dependent response to forcings, we first consider climate changes on time scales longer than the thermal relaxation time of the climate system, which is the time needed for the ocean to warm or cool and ice sheets to melt or grow.

Paleoclimate

The best empirical information on equilibrium climate sensitivity is provided by climate variations of the past 200 000 years. That period is long enough to have major climate changes, including global temperature variations as great as 5°C. Yet it is recent enough that detailed information on climate can be extracted from terrestrial records.

Ice sheets in Antarctica, built up from snowfall year by year, preserve a record of atmospheric composition in tiny air bubbles. Temperature is inferred from the isotopic composition of the snow and other methods (Figure 3).



Despite the similarity of the CO_2 and temperature curves, it should not be inferred that the CO_2 "caused" the climate change. Indeed, the CO_2 changes generally lag slightly behind the temperature changes. Probably as the climate warmed, the ocean or land released more CO_2, implying that CO_2 was a positive climate feedback on these long time scales. The major instigator of these long-term climate changes is usually assumed to be periodic changes of the Earth's orbit (for example, the eccentricity of the Earth's orbit about the sun and the inclination of the Earth's spin axis to the orbital plane), which alter the seasonal and geographical distribution of sunlight on Earth.[19] The role of orbital changes continues to be debated, especially issues regarding the timing of the orbital and climate changes.[44] Chaotic (unforced) fluctuations must also contribute to the climate changes.

The important factor is that climate sensitivity can be inferred by comparing the Earth's radiation balance during the ice age and interglacial periods, independent of the ultimate instigators of the climate changes.[14] Averaged over many years, say a few thousand years, the planet must be in radiation balance within a fraction of 1 W/m^2. This can be verified readily by calculating the amount of energy required to melt glaciers (Figure 4), even on continental scale, or to change the ocean temperature a plausible amount.

Figure 4.
An aerial view of Columbia Glacier. Alaska. The 1100-km^2 glacier has been in retreat since 1982 when a large embayment indicated a weak spot. Since then the glacier has pulled back over 3 km and a broad fan of loose ice floats in front of its 5-km-wide face. In a few decades the Columbia may recede 30 km or more and expose a new fjord.
JOSEPH J SCHERSCHLL

Figure 5.
Surface conditions in August during the last major ice age, ~20 000 years ago.[9]

Ocean temperature change (°C)

- >2
- 0 to 2
- −2 to 0
- −6 to −2
- <−6

Land albedo (%)

- <20
- 20 to 30
- 30 to 60
- >60

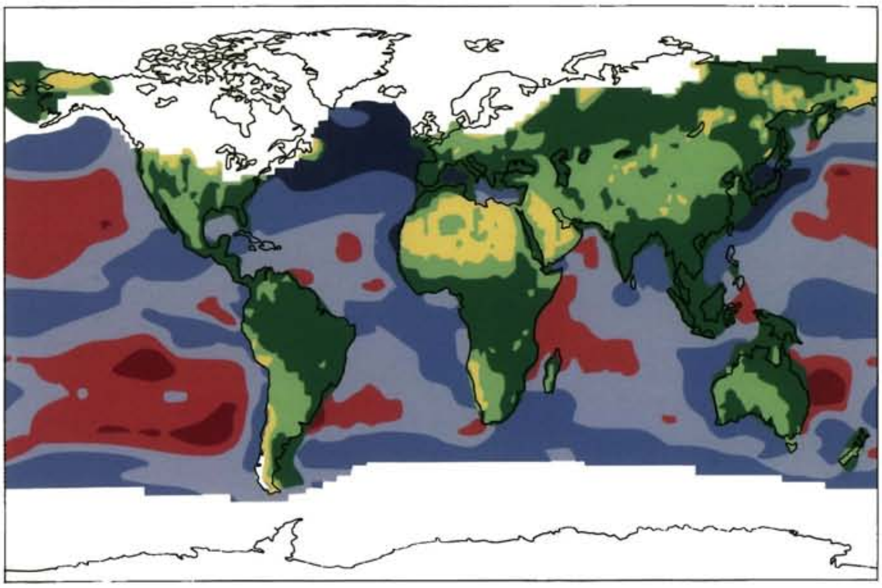
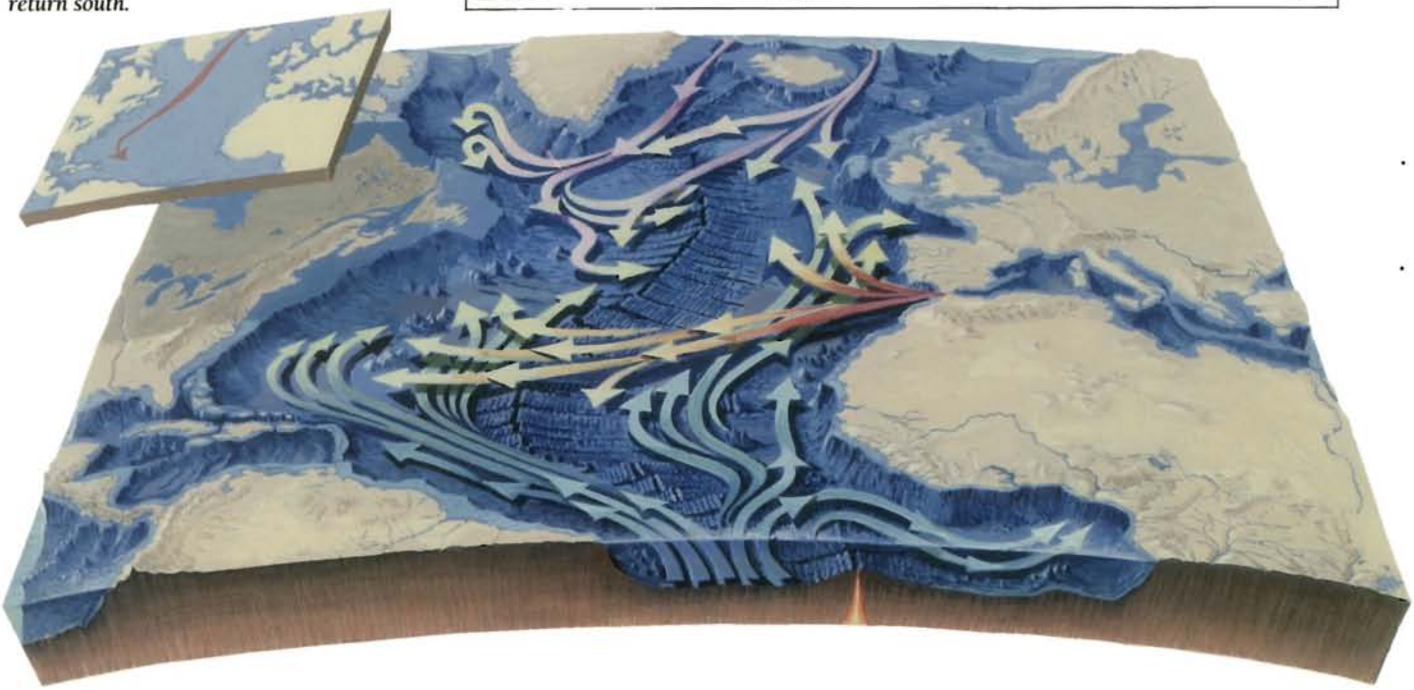


Figure 6.
Atlantic Ocean currents. Arrows indicate the flow of cold Arctic (lavender) and Antarctic (blue) waters that hug the ocean floor. Warm, salty Mediterranean water (red) stays at mid-depth; one component moves north, where it will mix, sink, and return south.



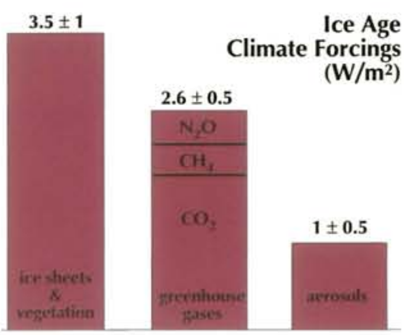
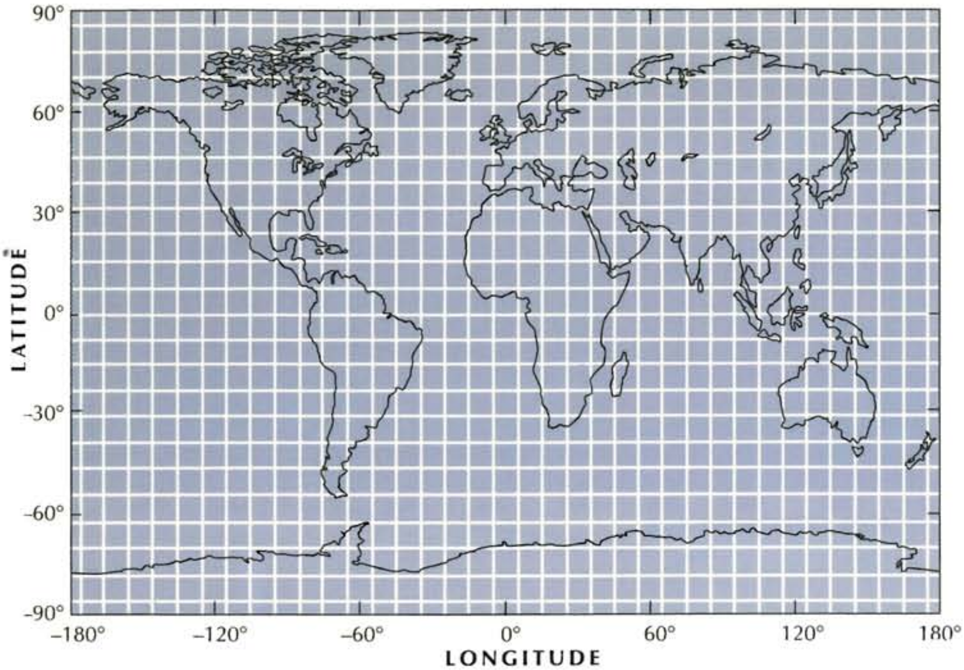


Figure 7.
Global climate forcings during the last ice age relative to the Holocene, ie, the past several thousand years. The total forcing is 7.1 ± 1.5 W/m^2. Thus the 5°C cooling of the ice age implies a sensitivity of 3°C for doubled CO_2 (4.2 W/m^2) forcing.

Based on knowledge of conditions during the last major ice age (Figure 5), we know the alterations on the Earth's surface and in the atmosphere that maintained the lower temperature, regardless of what caused the climate change. These were: increased reflection of sunlight by the continents, due to ice sheet growth and vegetation changes,[9,14] decreased greenhouse gases[27] CO_2, CH_4, and N_2O, and increased atmospheric aerosol particles,[5] which scatter sunlight to space. These surface and atmospheric changes caused a total forcing of 7.1 ± 1.5 W/m^2 (Figure 7).

Thus the actual global temperature change between the glacial and interglacial periods provides a measure of climate sensitivity. This empirical measure includes the "fast" feedback processes,[14] such as water vapor, cloud, and sea-ice feedbacks, processes that respond quickly to changed temperature and are included in current global climate models. But it also includes other feedbacks which may exist in the real world, for example proposed biogenic aerosol effects on clouds[7] and systematic alterations of the ocean's circulation (Figure 6).



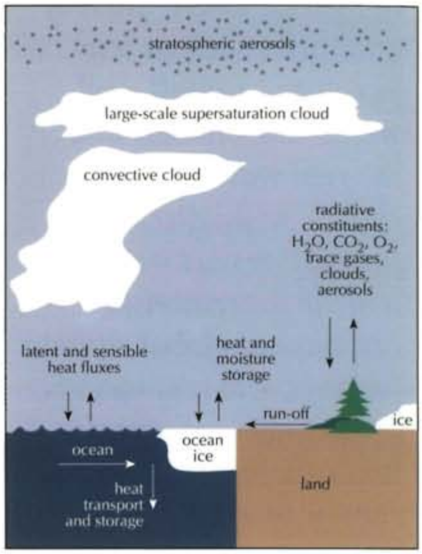


Figure 8. (left)
Global climate model grid at 7.8° × 10° resolution.

Figure 9. (above)
Several climate processes within a grid-box.

There is uncertainty about global temperature during the ice age. The CLIMAP reconstruction (Figure 5) has low-latitude ocean temperature little different from today's climate, leading to a global temperature 3.7°C colder than the current interglacial.[14] This is inconsistent with land evidence of 3 to 5°C cooling in much of the tropics.[36] New sources of data[2] suggest that CLIMAP may have underestimated low-latitude ice age cooling; global temperature was conceivably as much as 6°C colder than in the current interglacial.

We take 5°C as the best estimate of ice age cooling, which implies a climate sensitivity of 3°C for doubled CO_2 forcing (Figure 7). CLIMAP surface temperatures taken at face value imply a climate sensitivity of 2 to 2.5°C for doubled CO_2,[20] but the evidence for a colder tropics suggests a 2.5 to 4°C sensitivity. We conclude that the inferred climate sensitivity for doubled CO_2 at most approaches 4°C and at least exceeds 2°C.

There are many uncertainties and limitations in paleoclimate analyses. For example, chaotic long-term fluctuations in ocean heat transport can contribute to observed global temperature change. Also, climate sensitivity between the ice age and today may differ from that between today and a warmer world, although our analysis minimizes that factor by specifying ice sheet area and atmospheric composition as boundary forcings. The derived climate sensitivity, 3 ± 1°C for doubled CO_2, is a substantially narrower range than that obtainable from climate models alone. Paleoclimate studies are a potentially rich source of understanding about possible future climate change.

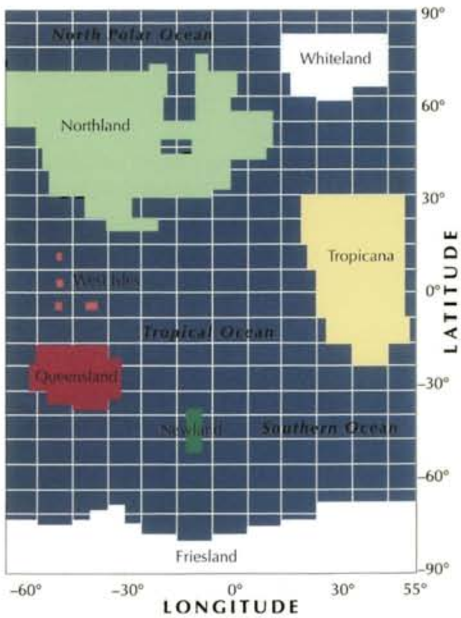


Figure 10.
Wonderland model geography.

Climate Modeling

A global climate model is based on fundamental equations, including conservation of energy, momentum, mass, and water, which are used to calculate quantities such as atmospheric winds, temperature, and precipitation. The world is partitioned by a grid (Figure 8) and the atmosphere and ocean are divided into many vertical layers. Within each grid-box are cal-

Climate models simulate the global distribution of quantities such as temperature, rainfall, and winds. The models and the real world exhibit chaotic unpredictable fluctuations, as well as a mean deterministic response to global climate forcings. Current models are primitive in simulation capabilities, and cannot provide reliable predictions for specific regions. But on the basis of general physical principles the models suggest[17] that global warming will intensify both extremes of the hydrologic cycle: heavy rainfall and storms (Figure 13) and droughts (Figure 14).

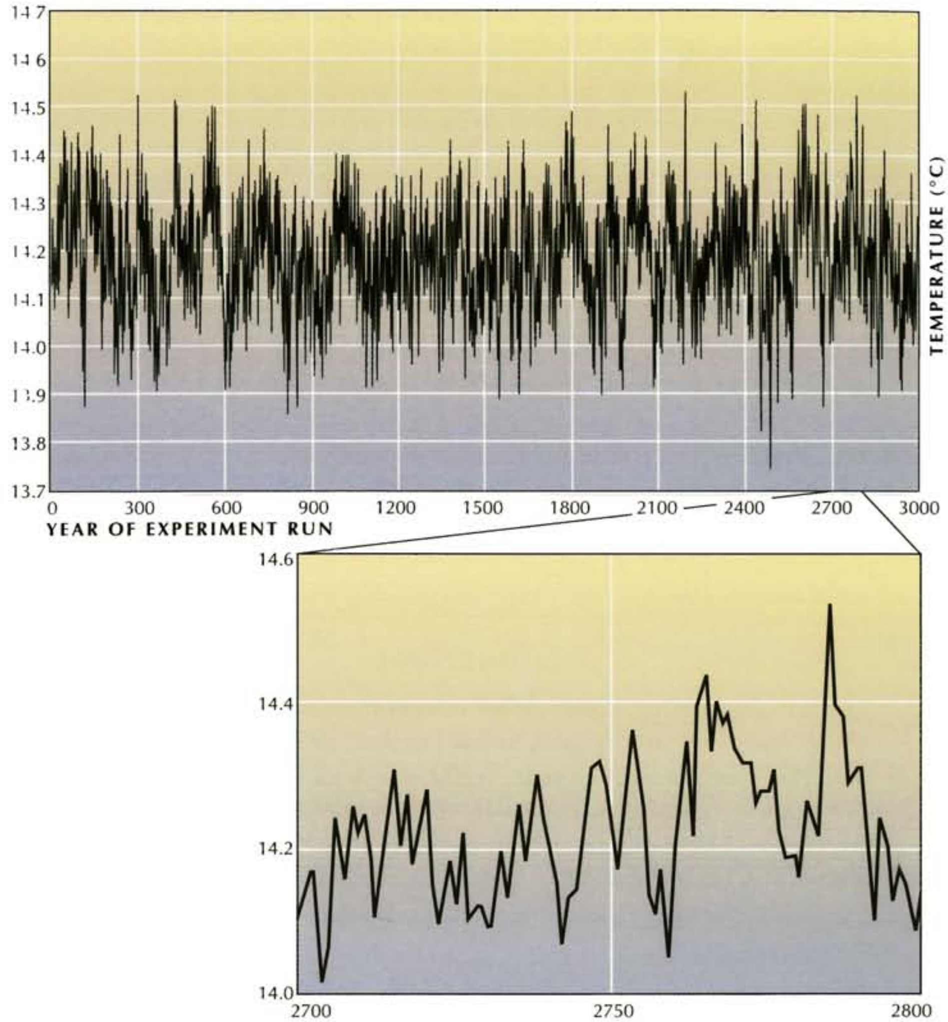


Figure 11. *(above)*
Unforced global temperature variations in a 3000-year run of the global climate model using the atmospheric composition of 1850 and a mixed-layer ocean of 250-m maximum depth.

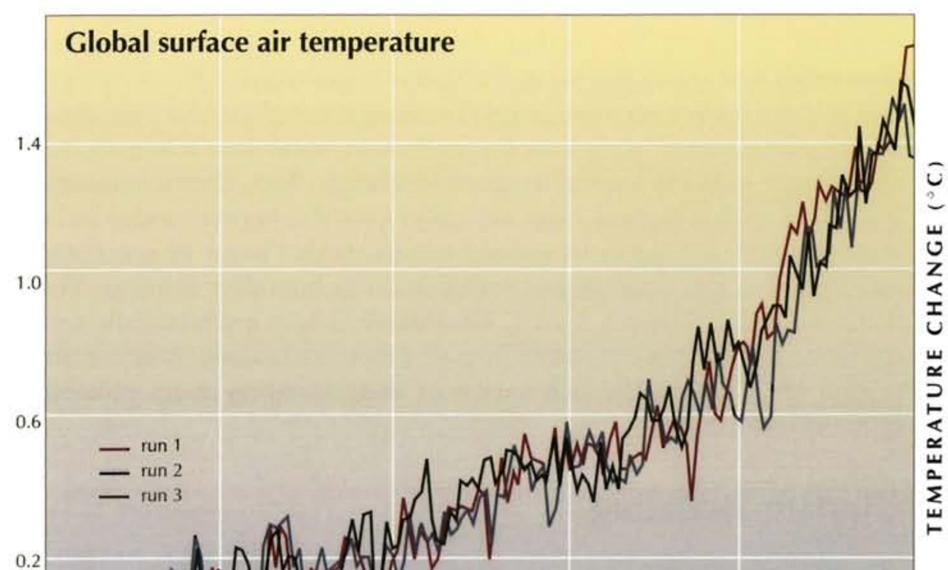


Figure 12.
Global temperature change in a global climate model due to measured increases of greenhouse gases (CO_2, CH_4, CFC, N_2O, and O_3). The model has a sensitivity of 4°C for doubled CO_2 and includes thermal inertia of the ocean beneath the mixed layer, with heat perturbations mixed as passive tracers. The 3 model runs have identical climate forcings. Interannual variability here, with a passive deep ocean, is 0.05°C, but use of a dynamic deep ocean[29] restores variability to 0.1°C of Figure 11.

Figure 13.
A 1983 cyclone on Arutua, Polynesia.
PHILIPPE MAZELLIER

Figure 14.
Drought at a Colorado farm. The severity of both storms and droughts have been predicted to increase with global warming.[17]
FRANK JOHNSTON

culated the effects of many processes that provide local sources and sinks of the variable quantities (Figure 9).

In some climate simulations we use an idealized ("Wonderland") geography (Figure 10) with the same proportion of land at each latitude as the real world. Wonderland has 120° of longitude, with cyclic conditions for the other 2/3 of the globe.[28] This model allows simulations over hundreds or even thousands of years with modest computer resources. The "physics" is nearly identical in the Wonderland and full world models, and the simulated climates are very similar.

A 3000-year run of the Wonderland model (Figure 11) illustrates chaotic fluctuations that occur without any changes of climate forcings. Global temperature varies by several tenths of a degree on time scales of years, decades, and centuries.

Repeated model runs, with slight changes of initial conditions but identical forcing, follow different paths (Figure 12) because of the climate's chaotic nature. Unforced variability of real climate is probably larger than that of the model, because our model keeps ocean horizontal heat transports fixed.[14] Thus ocean fluctuations such as discussed by W S Broecker,[3] which may affect global temperature as well as regional climate, are not included in the present model. Our model assumes that heat perturbations at the surface mix downward at a rate based on measurements of tracers such as tritium sprinkled on the ocean surface during atomic testing. Although dynamic ocean models are currently under intense development, they cannot yet provide a more realistic simulation of ocean heat uptake during the past century.

The Industrial Era

Inference of climate sensitivity from observed climate change during the industrial era is hampered by inadequacy of data on many climate forcings (pp 150 to 151). Present levels of homogeneously mixed greenhouse gases cause a forcing[13] 2.1 ± 0.3 W/m^2. Ozone depletion since the 1970s reduces the net greenhouse forcing by 0.2 ± 0.1 W/m^2 (Figure 15).

Stratospheric aerosols, produced by volcanos, cause highly variable forcing relative to the mean stratospheric aerosol amount. Its uncertainty is at least 25% in recent decades, and the values in the late 1800s, based

Sources of emissions to the atmosphere, and their visible effects:

- *El Chichon (right).*
- *Oil well fires in Kuwait (far right).*
- *Damaged trees in Germany's Black Forest (below).*
- *Industrial works at Linz, Austria, producing fertilizers and chemicals—as well as environmental concern (opposite page, upper left).*
- *Coal ash trapped in combustion chamber before being released into the atmosphere (opposite, upper right).*
- *Hohhot, Nei Mongol Zizhiqu (Inner Mongolian Autonomous Region), People's Republic of China. (1980) Smoke billows from the stacks of a suburban power station and steel mill in the background (opposite, below)*

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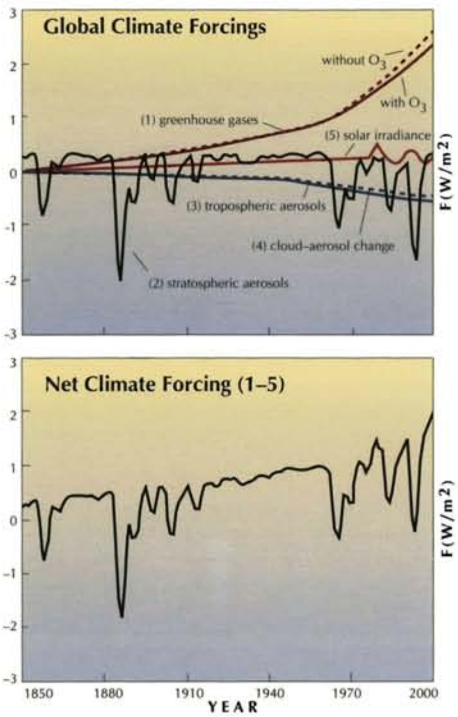


Figure 15.
Climate forcings used in GCM simulations, except the stratospheric aerosol forcing here is the 3-year running mean.

largely on astronomical observations of atmospheric transparency from a single station, are even more uncertain.[13,35]

Tropospheric sulfate aerosols from fossil fuel burning[8] and smoke from biomass burning[26,34] cause a negative forcing (cooling). Our calculated sulfate forcing is based on the aerosol geographic distribution of R J Charlson and coworkers,[6] which yields global mean anthropogenic sulfate optical depth 0.017 in 1990 (Figure 16). Smoke is approximated as having the same global mean optical depth as anthropogenic sulfate,[34] but is located over and downwind of tropical land. Time dependence of the optical depth follows SO_2 emission data of D Moller.[32] Aerosol single-scatter albedo is taken as 0.95 for sulfate, representative of measurements in regions of substantial aerosol amount, and 0.92 for smoke.[34]

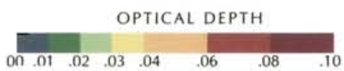
Cloud changes induced by anthropogenic aerosols are a very uncertain climate forcing,[1,8,10,25,40] because cloud brightness, cloud lifetime, and cloud cover are all affected. This forcing is typically estimated at ~0.5 W/m^2 globally, uncertain by at least a factor of 2. We multiply low-level cloud cover by the factor $(1+0.5\tau)$ where τ is the local anthropogenic aerosol optical depth, yielding a global mean flux of 0.45 W/m^2 in 1990.

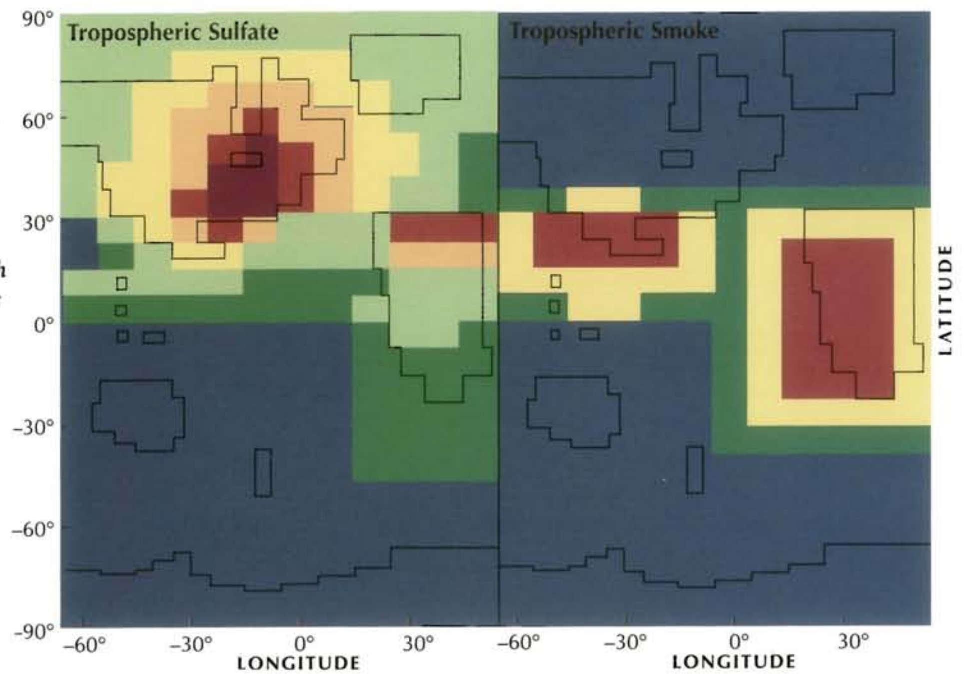
Solar irradiance varied by 0.1% in the last solar cycle,[43] too small and rapid a variation to be important climatically.[13,42] The main issue is whether there are larger long-term variations. J Lean[24] has suggested an approximately linear increase of 0.24% in the solar irradiance in the past 300 years. Because of the great uncertainty about solar change, we also use the solar variability suggested by D Hoyt and K Schatten[21] (Figure 17), which is qualitatively similar to solar variability inferred by several others.[11,23,37]

Apparently greenhouse gases are the dominant long-term forcing, but others are also substantial (Figure 18). The importance of the other forcings is increased by the fact that they mostly combine in the same sense (cooling), opposing the greenhouse warming. Firmer quantitative conclusions are prohibited by the lack of adequate global observations.

We carried out a series of simulations with the Wonderland model, adding climate forcings one by one and making simulations for 3 climate

Figure 16.
Geographical distribution of 1990 aerosol optical depths in Wonderland model. Optical depth τ is defined such that a beam of sunlight incident vertically on the atmosphere is reduced, due to aerosol scattering and absorption, by the factor $e^{-\tau} \sim 1-\tau$. Sulfate global and zonal amounts are from Figure 16 of Charlson and coworkers,[6] with a similar spatial dispersion over land at the same latitudes of Wonderland. Smoke has the same global mean τ as sulfate, and is dispersed in tropical regions as shown.





sensitivities. The lower sensitivities (1.5 and 0.5°C for doubled CO_2) were obtained by inserting a negative cloud feedback. Specifically the cloud cover was multiplied by the factor ($1+c\Delta T$) where ΔT is the deviation of global mean temperature from that in the control run with 1850 atmospheric composition, and c is an empirical constant (c=0.05 and 0.2 to obtain 1.5 and 0.5 sensitivities, respectively).

The results (Figure 19) show that the more plausible climate-forcing scenarios (3, 4, 5, and 6) yield a net warming over the period of record reasonably consistent with observations for climate sensitivities in the range 1.5 to 4°C for doubled CO_2. However, a climate sensitivity of the order of 0.5°C is inconsistent with the observations.

The tropospheric aerosol and aerosol cloud forcings together reduce simulated Northern Hemisphere warming below that of the Southern Hemisphere, while observations show comparable warmings in the hemispheres. Because of observational uncertainties, natural climate variability, and other factors influencing the hemispheric response,[41] we cannot conclude that the net aerosol forcing of Figure 18 is an overestimate, but it cannot be much larger than that indicated.

Detailed spatial and temporal observations of climate change can help verify and evaluate climate forcings. For example, a principal discrepancy between observed warming in recent decades and that expected due to homogeneously mixed greenhouse gases has been the fact that observed warming reaches altitudes only ~12 km, while calculated warming extends to ~18 km.[14] But in our present calculations, which include ozone depletion (Figure 21), the warming reaches ~12 km. Changes of ozone profile must be monitored to confirm the magnitude of ozone climate forcing, but available data suggest that ozone depletion significantly alters the temperature profile.

Another important observation is change of the diurnal cycle of surface air temperature, specifically evidence that daytime maximum temperatures have increased much less than nighttime minimum temperatures in the past century.[22] Such an effect occurs in our simulations (Figure 20) as a result of 3 mechanisms: global warming from any cause, which increases atmospheric water vapor; increased atmospheric aerosols; and increased clouds associated with the aerosols. These mechanisms decrease solar heating of the surface and reduce thermal cooling. In the industrial region of Northland, where aerosol optical depth is 0.08 to 0.1 (Figure 16), the effect essentially eliminates daytime warming. The mean observed effect falls between that for the mean of all land in Wonderland and that for the industrial region. We suspect that actual cloud increases are greater than in this simulation. There also may be middle and high cloud increases, including effects of aircraft emissions (Figure 26), which would damp the diurnal cycle while having little impact on mean temperature. Adequate knowledge of cloud changes can be obtained only with measurements of much higher specificity and precision than those of current meteorological satellites.[18]

Although we cannot distinguish among the higher climate sensitivities on the basis of current warming, Figure 19 indicates that the situation may begin to change within 10 years. By 2000, assuming no large volcanic eruption in the interim, we should see noticeable global warming if climate sensitivity is relatively high. However, for this empirical determination of climate sensitivity to be accurate, we need improved data on the major climate forcings.

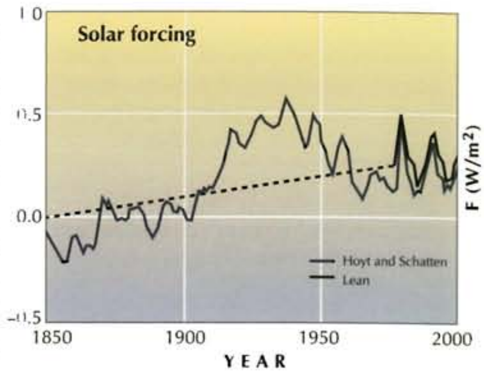


Figure 17.
Alternative climate forcings due to changes of solar irradiance, as suggested by J Lean[24] and D Hoyt and K Schatten,[21] with the final 2 decades based on observed irradiance change and extrapolations over the next solar cycle.

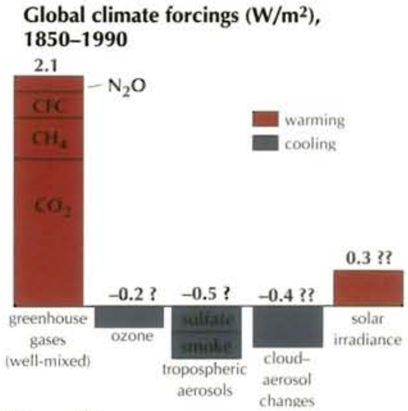
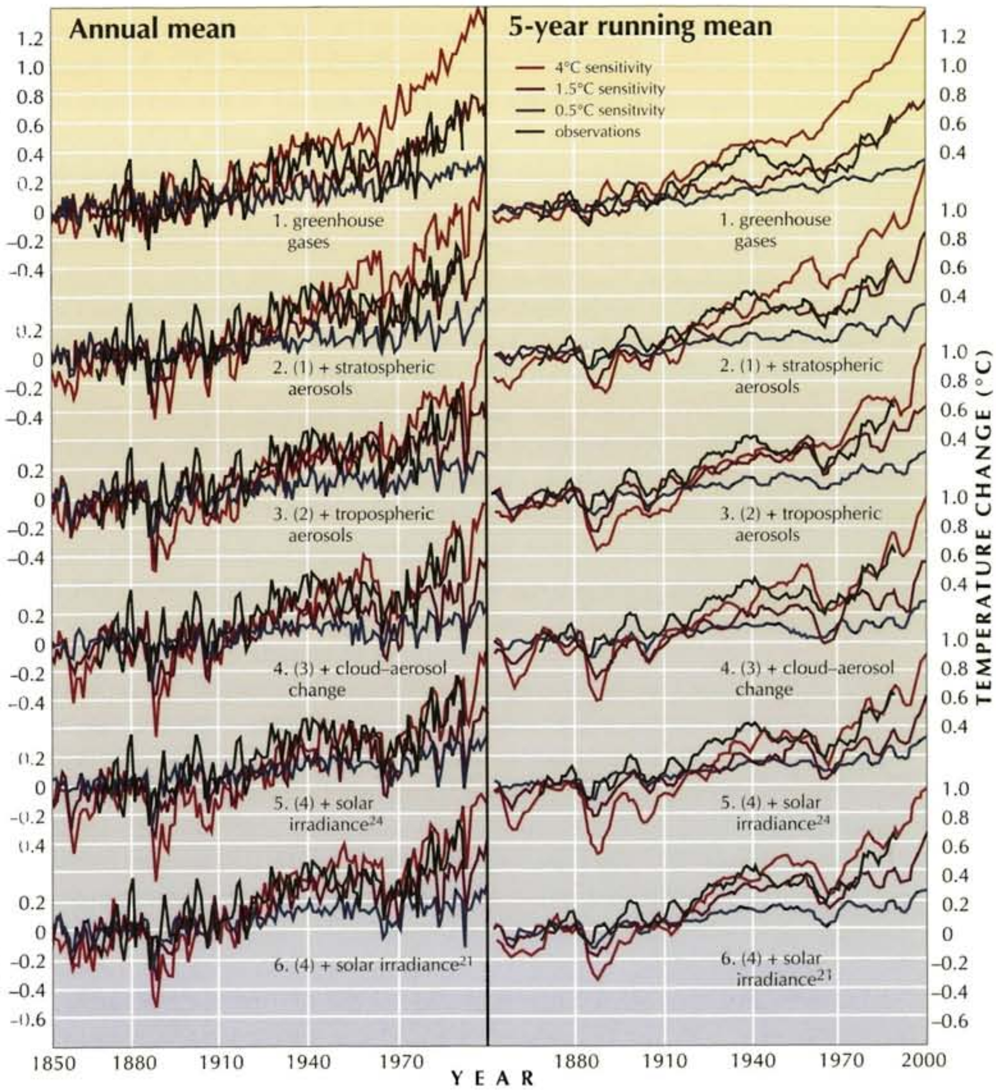


Figure 18.
Estimated climate forcings due to changes from 1850 to 1990.

Figure 19.
Simulated global temperature change for 3 climate sensitivities. Successive climate forcings are added cumulatively. Observed temperature record is an update of Hansen and Lebedeff[16] with a 0.1°C correction for estimated urban warming effect. The zero point of observations and model is 1866–1880 mean.



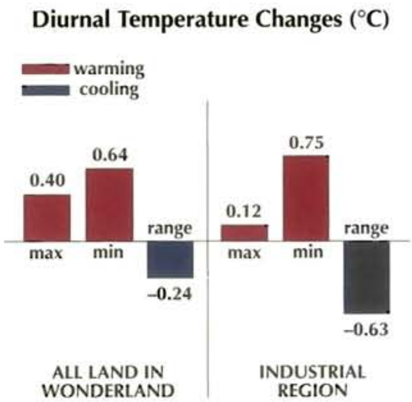
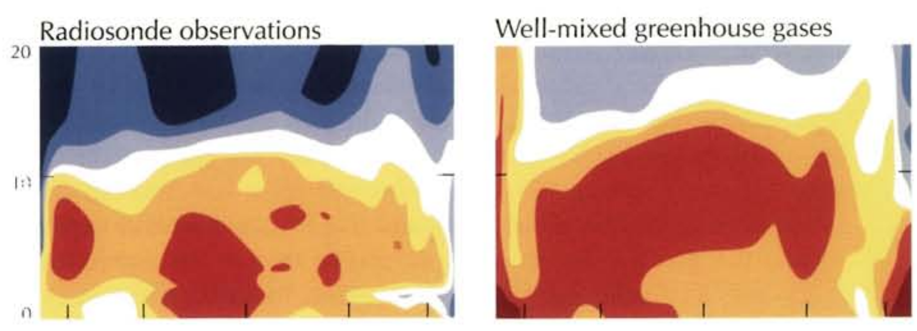
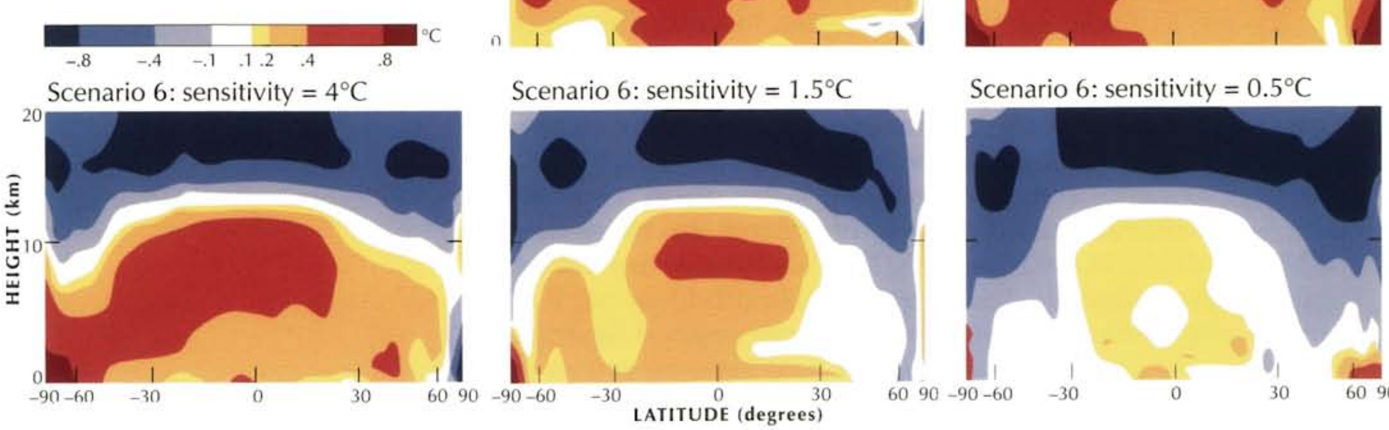


Figure 20.
Changes of daytime maximum, nighttime minimum, and diurnal temperature range in scenario 4 simulation with climate sensitivity 4°C (Figure 19). The industrial region is composed of the 5 gridboxes with aerosol optical depth 0.08–0.1 (Figure 16). Changes are the difference between the 1975–1995 mean and the control run.

Figure 21.
Zonal mean temperature change between 1963–1973 and 1986–1989. The observational data were supplied by A Oort of the NOAA Geophysical Fluid Dynamics Laboratory. The stratospheric cooling in scenario 6 (Figure 19) is caused by ozone depletion, which is based on satellite measurements of ozone column[38] and profile[30] changes.





Pinatubo

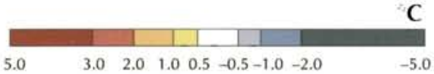
The eruption of Mount Pinatubo (Figure 22) in the Philippines injected ~20 million tons of SO_2 to heights of 25 km, producing what may be the largest global climate perturbation of the century. Dispersed by stratospheric winds, the SO_2 was photochemically transformed to sulfuric acid, forming a global layer of small droplets (aerosols). The stratospheric aerosols scatter sunlight back to space and absorb terrestrial heat radiation, thus cooling the lower atmosphere and warming the stratosphere.

Climate forcing by Pinatubo aerosols[15] reached a magnitude of ~4 W/m^2, and should remain significant for ~2 years. Thus nature has launched her own climate experiment, with a forcing temporarily exceeding that of anthropogenic greenhouse gases. The Pinatubo eruption provides a so far unique opportunity to test climate model performance. The eruptions of Agung in 1963 and El Chichon in 1982, the largest eruptions in the previous 75 years, were less strong and less well-observed, with only about half the climate forcing of Pinatubo.

Pinatubo already provides a valuable check of the global response to a large climate forcing. The climate impact was projected shortly after the eruption with one of the same models used to predict greenhouse climate

Figure 22.
Ash column generated by the eruption of Mount Pinatubo at 0851 on 12 June 1991. Column height is ~11 km.
D H HARLOW

Figure 23.
Observed surface air temperature anomalies, relative to 1951–1980 mean, for Northern Hemisphere summers of 1991 and 1992.



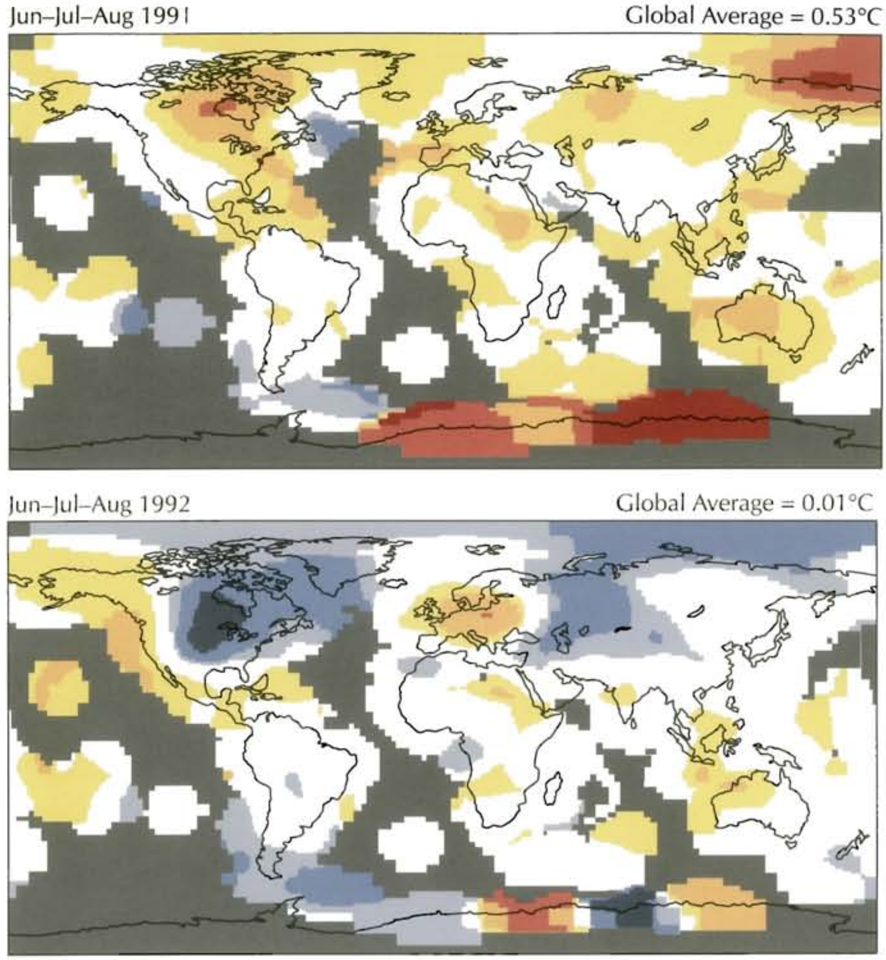
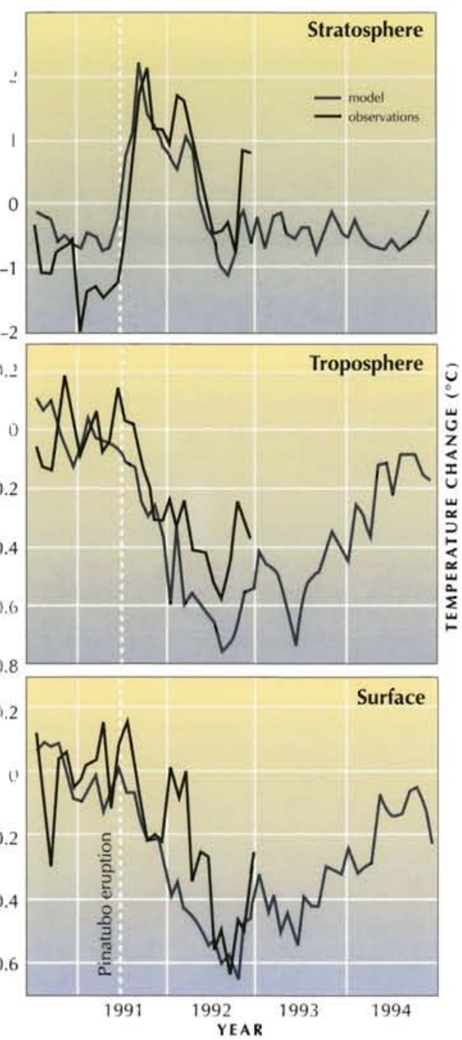


Figure 24.
Observed and modeled[15] (mean of 2 runs) monthly temperature changes. Stratospheric and tropospheric observations, obtained by satellite, are from M Gelman of NOAA and J Christy of the University of Alabama, respectively. Stratospheric observations are the 30-mb zonal mean temperature at 10°S; model results are the 10- to 70-mb layer at 8 to 16°S. Other results are essentially global, with observed surface temperature derived from meteorological stations.[16] Zero for stratospheric temperatures is 1978 to 1992; the troposphere and surface are referenced to the 12 months preceding the Pinatubo eruption.



effects.[15] Preliminary satellite data[31] for the radiative flux perturbation at the top of the atmosphere show promising agreement with the model, providing a fundamental verification. Observed global temperature change (Figure 24) exceeds normal variability, and the annual mean surface cooling of ~0.3°C in 1992 may increase to ~0.4°C after correction for El Niño warming. Calculated cooling (Figure 19) ranges from ~0.2°C for climate sensitivity 0.5°C to ~0.4°C for sensitivity 3 to 4°C. Thus it appears that the Pinatubo cooling favors high climate sensitivity, consistent with the empirical results for longer time scales, but full exploitation of the Pinatubo experiment requires more complete data and analyses.

The global pattern of temperature change after Pinatubo will provide a check on the ability of models to simulate regional climate change. Northern Hemisphere summer, when regional "noise" or natural variability is least, may be best for this (Figure 23). Summer 1992 cooling was greatest in the continental interiors, consistent with the small continental heat capacity, with some warming of the western boundaries. This regional pattern is qualitatively similar to the more extreme "year without a summer," 1816, following the Tambora eruption of 1815.[39] We suspect that higher than normal mid-continent atmospheric pressures associated with aerosol cooling play a role by causing a tendency for more southeasterly winds on the western coasts, and northerly winds farther eastward.

The post-cooling climate rebound after Pinatubo will provide a check of a fundamental science issue with policy implications: the degree to which the climate system is currently out of equilibrium with radiative forcings.[14]

If climate sensitivity is high, there is currently unrealized warming due to past changes of atmospheric composition, delayed by the long response time associated with high climate sensitivity.[14] Our estimates of climate sensitivity and climate forcings (Figure 18) imply an unrealized warming of at least ~0.5°C and a net incoming radiative flux of at least ~0.5 W/m^2. This substantial inferred radiative imbalance is the basis by which we predict (Figure 25) a rapid recovery from Pinatubo cooling and new record temperatures within the 1990s (Figure 19), despite conventional wisdom that natural climate variability prohibits reliable forecast of the short-term climate trend. New record global temperatures in the 1990s, if realized, will be evidence in support of the high climate sensitivity inferred from paleoclimate data, but quantitative interpretation will depend upon measurement of all major climate forcings.

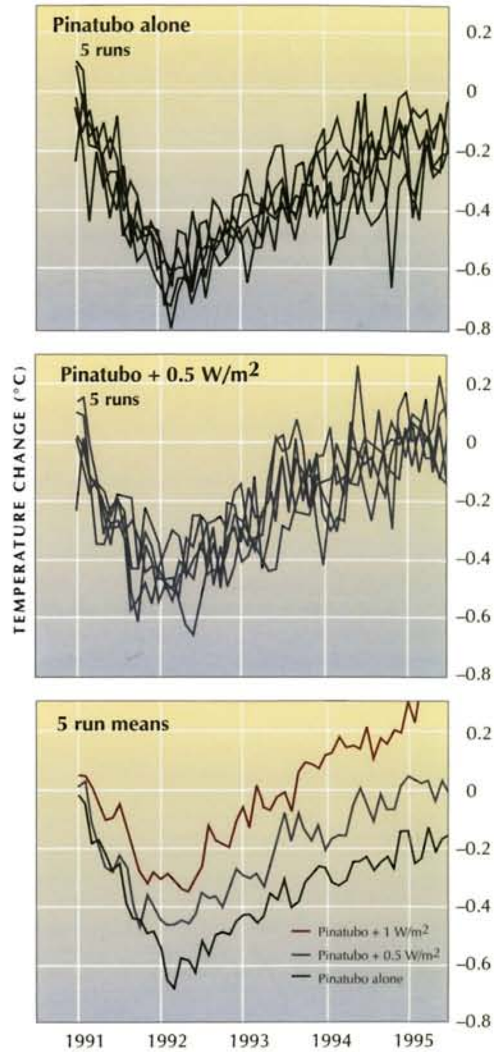


Figure 25.
Simulated global temperature changes for Pinatubo aerosols alone, and for Pinatubo plus greenhouse forcings of 0.5 and 1 W/m^2. The simulations do not include ocean fluctuations, such as El Niños and La Niñas, which approximately double the "noise" in global temperature. Other expected climate forcings in this period, such as increasing greenhouse gases (warming), further ozone depletion (cooling), and a declining solar cycle (cooling), will probably be smaller and partially offset each other.

Summary

In view of the immense power of natural weather and climate fluctuations and the great buffering capacity of the Earth, especially the ocean, it is easy to be skeptical about whether small anthropogenic changes of atmospheric composition can have important practical impacts. But quantitative evaluation shows that in recent decades climate forcings attributable to humans have reached a level comparable to Nature's forces of global change. This gives urgency to understanding how sensitive the climate is to any forcing.

We have used empirical evidence from different times scales to show that the climate system is indeed very sensitive to global forcings of a few W/m^2. Specifically, the data imply that doubling atmospheric CO_2, with other forcings unchanged, would lead to an eventual 3 ± 1°C global warming. Such a change would make the Earth warmer than it has been in hundreds of thousands of years.

Although many current climate forcings are not being measured accurately, the available data indicate that increasing greenhouse gases are the principal forcing and probably the cause of global warming of the past century. The dominance of greenhouse forcing over its chief competitor, anthropogenic aerosols, will increase in the future, because the long-lived gases accumulate while aerosols depend on the rate of fossil fuel and biomass burning, which must eventually level off.[13] Given the difficulty of predicting the exact consequences of large climate change, an appropriate strategy now is to minimize the ultimate anthropogenic climate forcing through actions that make good sense anyhow, such as improved energy efficiency.

Consideration of more drastic action depends upon additional empirical evidence of anthropogenic global climate change. Our climate simulations suggest that such evidence may begin to be available within the next 10 years, but it can be interpreted only if the principal global climate forcings and feedbacks are monitored. Such monitoring is feasible with space-borne instruments in appropriate orbits, making precisely calibrated measurements of reflected solar and emitted thermal radiation, since all forcings and feedbacks operate by altering these spectra.[18] But plans for appropriate monitoring are not in place, and the beginnings of a crucial multidecadal record of solar variability are in danger of being lost.[33] Unless monitoring plans are rectified, fundamental uncertainties about the causes and implications of observed climate trends will persist indefinitely.

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Figure 26.
A plane takes off at Edwards Air Force Base, California.
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