

GLOBAL WARMING

What Does the
Science Tell Us?

EXECUTIVE SUMMARY

George C. Marshall Institute
Washington, D.C.

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1. TECHNICAL ISSUES

Scientists affiliated with the George C. Marshall Institute have undertaken an examination of the observational and theoretical evidence pertaining to the global warming problem, prompted by a growing sense of alarm over the "greenhouse threat" among scientists, governments and the general public. This summary contains highlights from the results of their analysis.

One of the main reasons for public concern is the fact that the temperature of the earth has gone up approximately half a degree Celsius in the last 100 years. The increase coincided with a substantial increase in the amount of carbon dioxide and other greenhouse gases in the atmosphere. The increased concentration of these greenhouse gases is apparently the result of human activity, such as the burning of coal, oil and gas.

Several scientific groups have concluded that manmade emissions of carbon dioxide and other greenhouse gases are the cause of much or all of the rise in global temperatures that has been observed since the turn of the century. They predict that if the atmospheric concentration of greenhouse gases continues to increase, the average temperature of the earth will rise in the 21st century by at least 1.5–4.5°C, or as much as 8°F.¹

According to these scientific groups, a significant temperature rise could lead to recurrent and severe summer drought in the midwestern states of the United States and other productive agricultural regions. The worst-case scenarios predict a rise in sea level by as much as 15-25 feet² as a result of the greenhouse warming, inundating areas of New York, Miami and other coastal cities as well as low-lying river deltas and islands such as the Maldives. The lives of hundreds of millions of individuals would be disrupted.

Simulation of Global Climate by Computer Programs.
How accurate are the forecasts on which these predictions are

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based? Scientists trying to forecast the amount of warming resulting from an increase in greenhouse gases face the problem that the manmade warming effect they are calculating is quite small compared to many natural warming and cooling effects that influence the earth's climate. To treat this small manmade effect with a useful degree of accuracy, they must be able to compute the natural changes in the earth's climate with great precision.

The calculations that attempt to achieve this precision are performed with a computer model of the earth and its oceans and atmosphere. The model consists of equations that imitate mathematically the forces controlling the earth's climate. These equations are transcribed into a lengthy computer program with tens of thousands of lines of code.

One part of the mathematical program, for example, describes the flow of heat from the sun downward to the earth's surface, and the flow of heat back up again to space from the ground. This section of the computer code would include the effect of the greenhouse gases in the atmosphere in blocking the upward flow of heat and warming the planet. It would also include attempts to describe the effect of clouds on the climate, both in blocking the upward flow of heat and warming the planet, and in blocking or reflecting sunlight from above, and thus cooling the planet.

Another set of equations in the computer attempts to describe how large masses of air flow around the earth, from the continents to the oceans and vice versa. Additional equations check the humidity of the moving masses of air, and mathematically form clouds in the computer when the humidity approaches 100%. How realistically the clouds are simulated in the computing program has a major impact on the predictions of the amount of greenhouse warming. As noted below, clouds are the largest source of error in current climate forecasts.³

Still other equations describe how the heat coming down from above is absorbed by the oceans, and how quickly this heat is transferred to the deeper waters of the oceans. Accuracy in these last equations is also critical, because they determine whether the earth warms slowly or quickly in response to an

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increase in carbon dioxide and other greenhouse gases. Information on the speed with which the greenhouse effect will set in is a vital part of the climate scientist's input to policymakers.

In all, upwards of 20 basic and supporting equations are programmed for the computer to create a mathematical simulation or "model" of the earth's climate. The model's predictions also depend on dozens of parameters or "constants" whose values are assumed at the start of the computation. Some are accurately known as a result of observations; for others, including some of great importance, the climate modeler has to guess the right value.

The computations are exceedingly complicated, not only because they involve so many equations and parameters, but also because the whole system of equations is locked together by the "feedback" terms which make each equation dependent on one or several of the others. As a result, a computation of the simulated climate for the next 100 years can require as much as 10,000 trillion individual bits of arithmetic.

Importance of Computing Power. Greenhouse forecasts could be made both more accurate and more timely—and, therefore, more useful to policymakers—if the leading climate forecasting groups had more powerful computing facilities for their work. Supercomputers now on the market offer a 15-fold speed increase over the best computers now used by scientists working on the greenhouse problem. Even faster computers are under development. The Department of Energy announced a plan in 1990 for an eventual 10,000-fold increase in the performance of climate-forecasting computers.⁴

These supercomputers can diminish errors and uncertainties in the global forecasts resulting from inadequate allowance for the effect of ocean currents. They will also allow greenhouse forecasters to make the first serious attempts at useable regional forecasts—an achievement not within their grasp at present. The availability of substantially greater computing power should lead to dramatic improvements in the accuracy of regional forecasts and the overall pace of progress in global warming research.

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Critically important policy decisions affecting the five-trillion-dollar U.S. economy depend on the reliability of the predictions generated by the greenhouse forecasting groups. One hundred million dollars would purchase top-line super-computer complexes for the four major scientific groups working intensively on the greenhouse problem. The expenditure would be a solid investment in the future of the economy.

Clouds and the Greenhouse Problem. Clouds cover roughly half the earth's surface at any given time, shielding this large area from the sun's rays. As a consequence they have a cooling effect on the climate. Clouds also have a heating effect because, like greenhouse gases, they block the upward flow of heat to space from the earth's surface. However, recent satellite measurements have shown that while individual clouds have various effects that can contribute either to heating or cooling, the overall effect of the earth's cloud cover is to cool the planet.⁵

Clouds create a problem for the greenhouse forecaster because the overall natural cooling effect noted above is ten times larger than the manmade greenhouse warming projected for the middle of the next century.

Because the effect of the natural background of clouds on the input of heat to the earth's surface is so much larger than the predicted greenhouse effect, a small change in the cloud cover can either diminish the manmade greenhouse warming by a very large amount, or magnify it by a very large amount.

However, small changes in cloud cover are very hard to predict. Consequently, clouds make the greenhouse effect extremely difficult to predict with even the roughest degree of accuracy. They are the largest single source of error in the greenhouse forecasts.

A recent (1989) study published by the U.K. Meteorological Office (UKMO)⁶ illustrates the large changes in forecasts of global warming that result from seemingly modest changes in the way clouds are handled in the computations.

The UKMO computation of global warming refined this simple description of clouds and cloud formation by allowing

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for variations in the concentration of water droplets in the clouds making up each cloud-covered region. This seemingly minor change can have a large effect on the greenhouse problem, because a dense cloud—i.e., a cloud with a high concentration of water droplets—reflects a large fraction of incoming solar radiation, and thus is more effective than a thin cloud in screening the earth's surface from incident sunlight.

In other words, such water-heavy clouds (which often have a fleecy, white appearance to the eye because they reflect so much sunlight) tend to cool the earth. If more of these bright, water-heavy clouds appear in the atmosphere in response to the initial greenhouse warming, they will cool the planet and cut down the magnitude of the warming, acting as a negative feedback.

Introducing these and other elements of the real world into the computing program turned out to have a very large impact on the global warming predictions. The cloud feedback magnifies the small initial greenhouse warming that occurred in direct response to the addition of CO₂.

The changes reduced the greenhouse warming computed by the UKMO scientists by more than a factor of two—from 5.2°C to 1.9°C.* The UKMO treatment of cloud feedback is far from the last word on this subject. However, the fact that a moderate change in one aspect of the greenhouse computation produces such a large reduction in the predicted amount of global warming, confirms the suspicion that current predictions of the size of the greenhouse effect are extremely fragile.

Limited Value of the EOS Satellites for Greenhouse Research. The measurement of cloud properties emerges as a key requirement for improved computer forecasts of global warming. Other critical atmospheric variables, in addition to clouds, that require monitoring for improved climate forecasting in-

* These results refer to the case in which the CO₂ concentration is doubled at the start of the calculation. The computer models are then used to calculate how much the global average temperature rises in response to this increase in carbon dioxide.

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clude aerosols,* ozone and upper tropospheric and stratospheric water vapor. Aerosols are important because they screen the earth's surface from the sun and tend to cool the planet. Ozone and atmospheric water vapor are important greenhouse gases that tend to heat the planet.

The key climate-related observations required for improved accuracy of global warming predictions are included in the plans for EOS, the satellite-based Earth Observing System under development by NASA.

The EOS satellites are also designed to provide information on many other earth science disciplines in addition to climate science—*inter alia* geology, hydrology, meteorology, oceanography, earth resources and biological productivity. This circumstance limits the usefulness of the EOS satellites in current research on climate change. The provision for instruments covering nearly the full spectrum of earth science disciplines has the consequence that the EOS satellites are large, complex, vulnerable to single-point failure and exceedingly expensive, and—most important for the global warming problem—many years elapse before the data begins to flow.

Although planning for EOS started in 1986, the first two EOS satellites are not scheduled for launch until late 1997 and 1998. These launch dates seem almost certain, in the light of past experience with large space programs, to slip into the 21st century. But a stream of data that only commences to flow on or after the turn of the century will come too late to meet the needs of policymakers pondering the wisest course to follow in the face of conflicting and ambiguous scientific evidence. This extended number of years to launch essentially eliminates the usefulness of the EOS satellite as an input to government policy decisions on global warming.

A Network of Small and Inexpensive Satellites. The limitations of the EOS satellites for resolution of the global warming uncertainties can be overcome by the launch of a network of

* The particle content of the atmosphere, contributed mainly by volcanic dust, manmade pollution and biological activity.

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small and relatively inexpensive satellites, specifically designed to supply the key observations needed by the climate-forecasting community. A network of such climate-specific satellites, called CLIMSATs, has been proposed by climate scientists Hansen, Rossow and Fung.⁷

Each CLIMSAT would carry the same set of instruments—a minimal package needed to fill in the gaps in existing observing programs for clouds, aerosols and other key quantities. The individual instrument packages would weigh less than 200 kilograms, could be placed on a satellite with a mass of approximately 1000 kilograms (vs. 15,000 kilograms for EOS), could be launched on an off-the-shelf rocket of Delta class and would cost roughly \$100 million for instruments plus satellite (vs. \$3 billion for EOS).

A network of six CLIMSATs would provide global monitoring of clouds and other variables every four hours on the average, and would cost less than \$800 million, including launch costs. The instruments proposed by Hansen and his colleagues have been tested in orbit in previous missions and require little or no further development. The network could be in orbit by 1994-1995 if the program is initiated in the near future.

The network of CLIMSATs would satisfy all the major requirements of a global climate monitoring network which are, by and large, not satisfied by EOS: timely initiation of the program in relation to the needs of the policy-making community, reasonable cost, and feasibility of replacement if a satellite is lost at launch or in orbit.

2. GREENHOUSE FORECASTS COMPARED WITH OBSERVATIONS

James Hansen and his colleagues in NASA have made theoretical estimates of the greenhouse temperature increase we should have seen in the last 100 years, based on what we know about the increases in carbon dioxide and other greenhouse gases. They get a theoretical result of roughly half a degree Centigrade, in agreement with the observations.⁸ This fact suggests that the greenhouse calculations are good enough so that we should pay attention to what the calculations predict for the next century. However, a closer look at the comparison between the greenhouse theory and the observations, shown in Figure 1, raises doubts about the significance of this agreement.

Global Temperature Changes. First, nearly all the observed temperature increase occurred before 1940. But most of the greenhouse gases were emitted into the atmosphere after 1940. How can greenhouse gases be the cause of a rise in temperature that took place before they existed? Clearly, they cannot. Some other factors must have caused part, and possibly a large part, of that half-degree warming.

Second, after 1940 the earth became *cooler*. Average temperatures went down, and continued to go down for the next 30 years, until the 1970s, when they started to rise again. Throughout the 1940-1970 period, greenhouse gases were building up very rapidly in the atmosphere. If the greenhouse effect had any substantial influence on climate, the world's temperature should have been going up at an accelerating rate in that period, as the concentration of the gases continued to build up. In-

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stead, the world became cooler. Scientists disagree vigorously over the size of the greenhouse warming, but one thing they all agree on is that the greenhouse effect cannot cause a cooling.

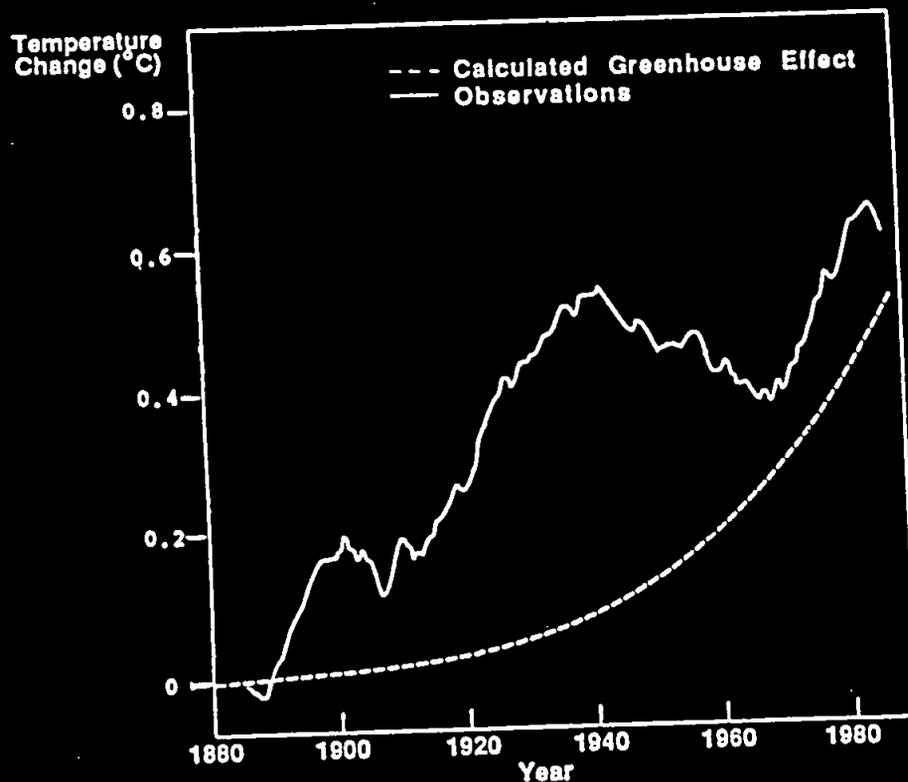


Figure 1. Comparison between observed global average temperature and calculations by Hansen *et al.*,⁸ based on a computer simulation of the greenhouse effect. The dashed line indicates the calculated temperature increase caused by carbon dioxide increases since 1880. The solid line indicates the observed temperatures for the same period. The zero point in the calculated curve has been adjusted to agree with observations for the 1880s, since nearly all the anthropogenic greenhouse warming occurred subsequent to that time.

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The calculations predict several other features of the greenhouse effect that distinguish it from other possible causes of global warming. A search for these distinguishing features provides an indication as to whether the calculations are correctly representing the magnitude of the effect.

Warming in the Northern Hemisphere. One distinguishing feature is a major difference in warming between the two hemispheres. All the greenhouse calculations predict more warming in the Northern Hemisphere than the Southern Hemisphere, as a consequence of the greenhouse effect. According to the calculations, the additional warming of the Northern over the Southern Hemisphere should already have amounted to about 0.5°C in response to the increase in greenhouse gases in the last 100 years.⁹ However, the observed temperatures, shown in Figure 2, show no significant difference in temperature trends in the two hemispheres in the last 100 years.¹⁰

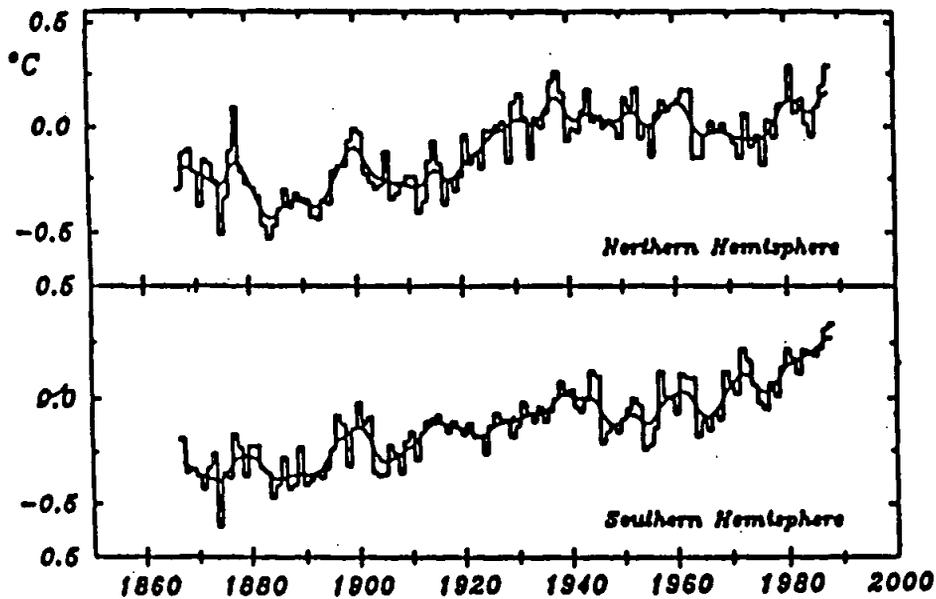


Figure 2. Northern and Southern Hemisphere temperature observations.

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Warming at High Latitudes. All the greenhouse computations predict an intense warming at high latitudes in the Northern Hemisphere, roughly twice as much as the warming for the tropical latitudes. The intensity of high-latitude warming in the Northern Hemisphere should be particularly noticeable in the observations for the years subsequent to 1940, since this was the period in which the bulk of the greenhouse gases entered the atmosphere. The observed temperatures, shown in Figure 3a, indicate no net warming at high latitudes after 1940.¹¹ Instead, a significant warming trend appears after 1940 in the *low-latitude* observations—a latitude dependence opposite to the predictions of the greenhouse calculations (Figure 3b).

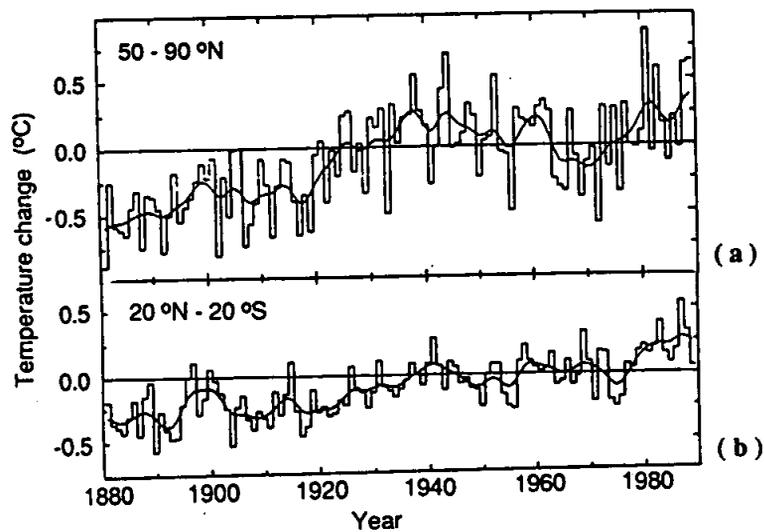


Figure 3. Observed variations in annual mean temperature in (a) high latitudes in the Northern Hemisphere and (b) the tropics.

Rapid Warming in the 1980s. The greenhouse computations indicate a rapid rise in temperatures in the 1980s, as a result of a large increase in the greenhouse gases in recent years. The results of the calculations for the 1980s, shown in Figure 1, show a

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rise of nearly 0.2°C—significant for a change taking place over only one decade.⁸

However, highly precise measurements of global temperatures for the 1980s carried out from satellites show no significant change during the 1980s.¹² These accurate satellite measurements contradict the prediction of a strong 1980s warming trend.

1990: Warmest Year in the Record? Measurements of surface temperatures taken on continents and islands around the globe indicate that 1990 was the warmest year in the history of temperature records.¹³ This finding is in line with greenhouse predictions of a rapid warming toward the present end of the century.

However, the finding is contradicted by satellite measurements of the earth's temperature, obtained by looking down at the planet from above. The satellite measurements give a more accurate picture of the average temperature of the planet than the surface measurements, because they cover the entire globe. The surface measurements have spotty coverage, with large gaps over the oceans and sparsely inhabited land areas.

The satellite results, listed in the table below, show no unusual temperature increase in 1990.¹⁴ In fact, the results show

SATELLITE TEMPERATURE MEASUREMENTS

Departures from the 1979-1990 mean

1979	+ 0.01
1980	+ 0.15
1981	+ 0.08
1982	- 0.14
1983	+ 0.12
1984	- 0.16
1985	- 0.26
1986	- 0.14
1987	+ 0.21
1988	+ 0.19
1989	+ 0.00
1990	+ 0.11

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that 1990, far from being the warmest year ever, ranks only 5th warmest year out of the last 12, i.e., it is in the *middle* of the range of temperatures measured in the last decade.

The list of satellite measurements also confirms that, as noted above, no significant warming trend appeared during the decade of the 1980s. Temperature increases in some years are balanced by cooling in others.

Warming Increases in the U.S. The greenhouse computations also predict that the continental U.S. should have become about 0.5°C warmer in the last 100 years. The temperature observations, shown in Figure 4, indicate there has been no trend to higher temperatures in the U.S. in that period.¹⁵ It is striking that in the largest area of the world for which reliable, well-distributed temperature records are available, the greenhouse predictions are not confirmed.

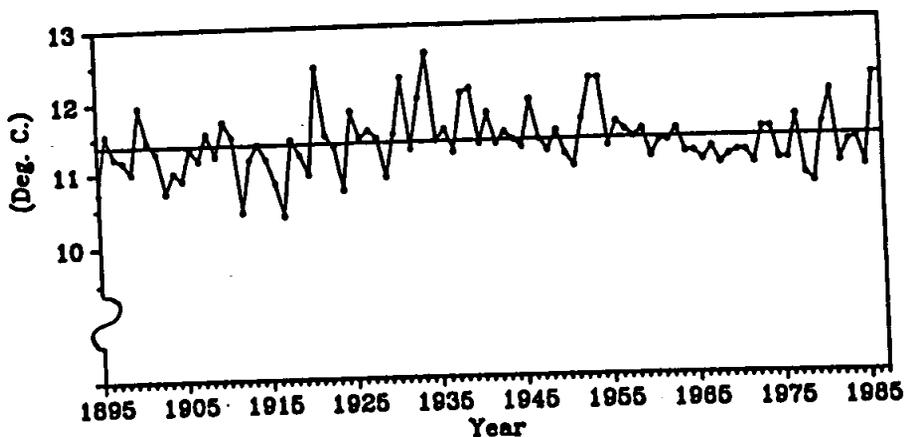


Figure 4. Annual average temperature for the contiguous United States 1900-1984, corrected for urban heat island effect.

The Greenhouse Fingerprint. According to the computer simulations of the earth's climate, a greenhouse-induced warming has characteristics which distinguish it from temper-

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ature changes produced by other factors. Among these properties, which constitute the fingerprint of the greenhouse effect, are: (i) a greater temperature rise in the Northern Hemisphere; (ii) a greater temperature rise at high latitudes than at low latitudes; (iii) an accelerating increase in temperatures in the 1980s, reflecting the rapid increase in greenhouse gases in recent years; and (iv) a substantial increase in temperature in the United States in the last 100 years.

All four predictions are contradicted by the climate changes that actually occurred in the last 100 years. The predictions yielded by the computer simulations of global warming appear to fail the test of comparison with observation in nearly every important respect. This does not inspire confidence in the ability of these computer forecasts to predict what will happen in the next 100 years.

Reasons for Poor Quality of the Greenhouse Forecasts.

How can the greenhouse calculations be so far off from the observations, and also so inconsistent with one another? The answer lies in the fact that these are not really "calculations" of temperature, as most laymen would interpret the word. A "calculation" sounds like a solid result: an engineer calculates the size of the girders needed to support the weight of the traffic on a bridge, for example. But the greenhouse "calculations" are different. They are not solid. As noted earlier, some twenty partial differential equations and supporting equations underlie the greenhouse "calculations" of global climate. In addition to dozens of so-called "constants," whose values are crucial to the forecasts but often have to be guessed, the whole system is locked together by feedbacks. The computer program takes tens of thousands of lines of code. A single computation of 100 years of simulated climate requires about 10,000 trillion individual bits of arithmetic.

This massive effort is an attempt at a computer simulation of an extremely complicated situation—the oceans, atmosphere and land areas of the earth, all interacting with one another—and to predict what will happen to this complicated system when one factor, like the amount of carbon dioxide in the at-

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mosphere, changes. Many of the critical interactions are poorly known. Some key interactions probably have not yet even been identified. It is not reasonable to expect this weak theoretical edifice to produce estimates of global temperature a century in the future with any useful degree of accuracy.

3. EMPIRICAL LIMITS TO GLOBAL WARMING

Is there a better guide to climate change than the computer forecasts? Can we give more reliable information to the policy-making community and the energy sector trying to plan intelligently for the future?

The real world has important information for the climate expert in this connection. In the last 100 years, the concentration of greenhouse gases increased by an amount equivalent to a 50% rise in carbon dioxide. Meanwhile, the temperature of the earth rose by roughly 0.5°C. Suppose we assume that the entire global warming of 0.5°C was caused by the greenhouse effect. Probably not all of it was. But let us assume that it was, to get started.

With that assumption, we can say that mankind carried out an experiment, and the results of the experiment are in hand: A 50% increase in carbon dioxide leads to a half-degree rise in global temperature.

This is a solid finding, because the clouds and oceans in that "experiment" were not computer simulations of clouds and oceans, but the clouds and oceans of the real world. The feedbacks in the "experiment" are the feedbacks in the real world. These feedbacks are the key factors in determining global warming, and are so complicated they have to be guessed at by the theorists, when they try to imitate the climate in the computer programs. An estimate of the coming greenhouse effect, based on this response of the real earth to real greenhouse gases, should be a better guide to future global warming than calculations based on the highly uncertain computer simulations.

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A Forecast Based on the Real World. How can the results of this global "experiment" be used to predict the magnitude of the greenhouse effect in the next century? According to projections of global energy use, between now and the mid to late 21st century the concentration of greenhouse gases is expected to increase by an amount equivalent, in climate impact, to roughly a doubling of carbon dioxide over today's levels.¹ If the greenhouse gas increase of the last 100 years, which was equivalent to a 50% rise in carbon dioxide, was the sole cause of the 0.5°C rise in temperature, an increase equivalent to a 100% rise, or doubling, in the concentration of carbon dioxide in the coming century should produce approximately twice as large a temperature change, i.e., a 1°C rise.

Sources of Uncertainty in the Forecast. How solid is the analysis leading to an estimate of a 1.0°C temperature rise in the coming century? That analysis depends on the assumption that the temperature rise observed in the last 100 years has been accurately measured and is, in fact, 0.5°C. If the observed increase of 0.5°C in the last 100 years is itself subject to possible error because of uncertainties in measurement and gaps in coverage, the prediction for the next century must be adjusted to allow for the fact.

The prediction also neglects the fact that the warming of the earth lags behind the actual increase in greenhouse gases because of the large heat capacity of the oceans. Because of this ocean thermal lag, the amount of greenhouse warming observed to date, is not the full warming that will eventually result from the greenhouse gases already in the atmosphere. The results of the analysis must be adjusted to allow for this effect.

Finally, the analysis depends on the assumption that the 0.5°C rise in the last 100 years was entirely the result of the greenhouse effect. If other factors besides the greenhouse effect have contributed to the 0.5°C rise, the analysis must be adjusted to allow for those factors.

Adjustment for Errors in the Temperature Observations. The IPCC report suggest that the nominal 0.5°C rise in global

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temperatures in the last 100 years should be replaced by a rise in the range 0.3–0.6°C, because of observational uncertainties.¹ Since the climate impact of greenhouse gases in the 21st century is expected to be double their impact in the last 100 years, the temperature increase produced by the greenhouse effect in the next century should lie in the range 0.6–1.2°C. This range in possible temperature increases replaces the initial estimate of 1.0°C.

Ocean Thermal Lag. Because of ocean thermal lag, the global temperature rise observed to date cannot be the full response to the greenhouse gas increase that has occurred in the last 100 years. The extent of the ocean thermal lag depends on the rate at which heat absorbed at the surface of the ocean is transferred from the shallow surface layer to the much larger volume of water at greater depth. Recent computations, with the effects of ocean circulation included, show that 3/4 of the full warming appearing in the first 10 years after an increase in greenhouse gases takes place.^{16, 17} From this result it can be estimated that the ocean thermal lag has reduced the warming to date by approximately 0.1°C. Accordingly, the IPCC estimate of a range of 0.3–0.6°C for the observed temperature rise should be increased to 0.4–0.7°C. Since the climate impact of increased greenhouse gases by the mid-to-late 21st century is expected to be double their impact in the last 100 years, the projected temperature increase in the mid-to-late 21st century is increased to the range 0.8–1.4°C.

Natural Factors in Climate Change. Theoretical studies of the natural variability of climate—substantial swings of global temperature occurring without apparent cause—indicate that this phenomenon can produce changes of the order of 0.2°C over a 100-year period,¹⁸ for climate models close to those used by the IPCC as the basis for its "best estimate" of global warming. The 0.2°C change due to natural variability can be in either direction; that is, the greenhouse contribution to the observed warming of 0.4–0.7°C over the last 100 years could have been as little as 0.2°C or as much as 0.9°C, after correction for natural

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variability. If the greenhouse impact by the middle of the 21st century is double the impact of the anthropogenic greenhouse gases to date, as the IPCC projection indicates, the global warming in the mid 21st century will lie in the range 0.4-1.8°C.

Empirical Limits on 21st Century Warming. This projection of global warming in the mid-21st century is derived from the temperature changes observed in the last 100 years, modified to allow for (i) uncertainties in the temperature observations to date; (ii) ocean thermal lag; and (iii) possible contributions of natural variability to the observed 1880-1980 rise.

The midpoint of the projected range 0.4-1.8°C is 1.1°C. This empirically based result is significantly lower than the IPCC "best estimate" of 2.5°C for the warming expected to occur in the same time period.

It should be noted that the IPCC estimate is based almost entirely on computer simulations of the earth's climate, whose predictions to date for the greenhouse effect disagree with observation in nearly every important respect. The limits 0.4-1.8°C derived above are based on the observations themselves, i.e., on the earth's known response to a known increase in greenhouse gases.

The low end of the estimate of 0.4-1.8°C would not have a significant impact on human affairs. The high end of the estimate—1.8°C spread over half a century or more—may or may not be significant in the sense of requiring governmental constraints on greenhouse gas emissions. Reduction of the uncertainty in the forecasts is clearly essential if useful information is to be provided to policymakers.

4. PRINCIPAL FINDINGS

According to computer simulations of the earth's climate, the global warming produced by the greenhouse effect has special characteristics which distinguish it from temperature changes produced by other causes. These characteristics, which constitute the fingerprint of the greenhouse effect, are contradicted by the climate changes that have actually occurred in the last 100 years.

As matters stand, it is difficult to place any degree of confidence in current attempts to simulate the earth's climate, and in their forecasts for the greenhouse effect in the coming century, considering how poorly these simulations have fared in accounting for changes observed during the past century.

An empirically based analysis of the future greenhouse effect, based on the actual response of the earth to the increases in carbon dioxide and other greenhouse gases that have occurred to date, should be a better guide to the coming global warming than forecasts derived from the highly uncertain computer simulations.

The result of the empirical analysis is a temperature increase of not less than 0.4°C , but not more than 1.8°C . This range of temperatures reflects uncertainties in global measurements to date and possible contributions from natural factors in climate change.

The upper limit to this empirically based result is significantly less than the IPCC "best estimates" of 2.5°C for the warming produced under similar assumptions. The IPCC estimate is based on computer simulations of the earth's climate, whose predictions for the greenhouse effect to date disagree with observation in many important respects. The upper limit to global warming in the present analysis is based on the earth's known

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response to the known increases in greenhouse gases that have already occurred in the last 100 years.

The lower limit to the empirically based range of temperature increases would not have a major impact on human affairs. The upper limit— 1.8°C spread over the better part of a century—may or may not be significant in the sense of requiring government constraints on greenhouse gas emissions. Further reduction of the range of uncertainty in the forecast is clearly essential if useful information is to be provided to officials concerned with development of a national energy policy.

Conclusions. Do we have time to carry out the research aimed at narrowing the uncertainty in current forecasts? Some scientists and policymakers say we do not. They say we have to move now; we cannot take a chance on waiting for more research and better forecasts. But the scientific facts do not support that position.

Much of the research reported in this volume has been conducted in the last two to three years. With the attention of scientists focused on the greenhouse problem, it seems very likely that significant additional progress will be made in the next 3-5 years. It has been suggested that the U.S. major policy decisions on carbon restraints be deferred for five years, while the research is conducted that can give public officials more reliable information. The calculations show that the most that can happen because of the delay is an additional 0.1°C of warming in the 21st century.

This would be a relatively small penalty for getting reliable information to government officials before they undertake to restructure the economy of the United States.

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