DOHERTY
RUMBLE
& BUTLER
PROFESSIONAL ASSOCIATION

Magruder Building
1625 M Street, N.W.
Washington, D.C. 20036-3203
Telephone (202) 293-0555
FAX (202) 659-0466

2800 Minnesota World Trade Center
30 East Seventh Street
Saint Paul, Minnesota 55101-4999
Telephone (612) 291-9333
FAX (612) 291-9313

3500 Fifth Street Towers
150 South Fifth Street
Minneapolis, Minnesota 55402-4235
Telephone (612) 340-5555
FAX (612) 340-5584

2370 One Tabor Center
1200 Seventeenth Street
Denver, Colorado 80202-5823
Telephone (303) 572-6200
FAX (303) 572-6203

Attorneys at Law

Reply to Washington, D.C. office

(244)

March 15, 1995

VIA FEDERAL EXPRESS

Dr. Burl W. Haar
Executive Secretary
Minnesota Public Utilities Commission
121 Seventh Place East, Suite 350
St. Paul, Minnesota 55101-2147

Re: In the Matter of the Quantification of Environmental Cost
Docket No. E-999/CI-93-583

Dear Dr. Haar:

Enclosed for filing on behalf of Western Fuels Association, Inc., Lignite Energy Council, the Center for Energy and Economic Development, and the State of North Dakota, please find an original and twelve copies of testimony in the above-referenced case. The larger notebook, labeled Carbon Dioxide Science Panel, contains the testimony of Dr. Frederick Seitz, Dr. Richard Lindzen, Dr. Robert Balling, Dr. Patrick Michaels, and Mr. Keith Idso. The smaller notebook, labeled Carbon Dioxide Policy Panel, contains the testimony of Mr. Philip Burgess, General Richard Lawson, and Mr. Jack Siegel. Concurrently with the filing of this testimony, we are supplying an original and one copy to Administrative Law Judge Allan Klein and four copies to the Department of Public Service. Judge Klein's package and the Department of Public Service's package each contain a disk in Word Perfect 5.1 format containing the above-referenced testimony.

Western Fuels Association, Inc., Lignite Energy Council, the Center for Energy and Economic Development, and the State of North Dakota are cosponsoring this testimony in order to present our carbon dioxide witnesses in a coordinated manner and, hopefully, to avoid duplication. We hope this format will make our carbon dioxide testimony more focused and understandable for the Judge and the Commission.

DOHERTY
RUMBLE
& BUTLER
PROFESSIONAL ASSOCIATION

Minnesota Public Utilities Commission
March 15, 1995

We are enclosing one copy of this letter that we ask that you have filed-stamped and return to me in the enclosed stamped and self-addressed envelope.

Thank you.

Sincerely,

Peter Glaser
Attorney for Western Fuels Association, Inc.

Enclosures

cc: All parties on attached service list

CERTIFICATE OF SERVICE BY MAIL

I hereby certify that on March 15, 1993, I served on all the parties herein by mailing, regular mail, postage prepaid, a true, exact and full copy of the testimony of each of the following: Dr. Frederick Seitz, Dr. Richard Lindzen, Dr. Robert Balling, Dr. Patrick Michaels, Mr. Keith Idso, Mr. Philip Burgess, General Richard Lawson, and Mr. Jack Siegel. Four complete copies have been sent by Federal Express to the Minnesota Department of Public Service.

Peter Glaser
Doherty, Rumble & Butler, PA
1625 M Street, N.W.
Washington, D.C. 20036-3203

Attorney for
Western Fuels Association, Inc.

BEFORE THE MINNESOTA PUBLIC UTILITIES COMMISSION

In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minn. 1993, Chapter 356, Section 3	))))	Docket No. E-999/CI-93-583

CARBON DIOXIDE SCIENCE PANEL

Dr. Frederick Seitz
Dr. Richard Lindzen
Dr. Robert Balling
Dr. Patrick Michaels
Mr. Keith Idso

Sponsored By:

Western Fuels Association, Inc.
Lignite Energy Council
Center for Energy and Economic Development
State of North Dakota

March 15, 1995

BEFORE THE MINNESOTA PUBLIC UTILITIES COMMISSION

In the Matter of the Quantification)
of Environmental Costs Pursuant)
to Laws of Minn. 1993,)
Chapter 356, Section 3)

Docket No. E-999/CI-93-583

RECEIVED
MAR 15 1995
MINNESOTA
DEPT. OF PUBLIC SERVICE

CARBON DIOXIDE SCIENCE PANEL

Dr. Frederick Seitz
Dr. Richard Lindzen
Dr. Robert Balling
Dr. Patrick Michaels
Mr. Keith Idso

Sponsored By:

Western Fuels Association, Inc.
Lignite Energy Council
Center for Energy and Economic Development
State of North Dakota

March 15, 1995

BEFORE THE MINNESOTA PUBLIC UTILITIES COMMISSION

In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minn. 1993, Chapter 356, Section 3	))))	Docket No. E-999/CI-93-583

REBUTTAL TESTIMONY OF DR. FREDERICK SEITZ

Sponsored By:

Western Fuels Association, Inc.
Lignite Energy Council
Center for Energy and Economic Development
State of North Dakota

March 15, 1995

REBUTTAL TESTIMONY OF DR. FREDERICK SEITZ

Q. Please state your name and business address for the record.

A. My name is Dr. Frederick Seitz. My business address is the Rockefeller University, 1230 York Avenue, New York, NY, 10021-6399.

Q. Please state your qualifications for presenting this testimony.

A. I am currently the President Emeritus of The Rockefeller University in New York City and Chairman of the Board of Directors of the George C. Marshall Institute. Rockefeller University, originally called the Rockefeller Institute for Medical Research, is principally a scientific university, founded by John D. Rockefeller, Sr. in 1901, devoted to advanced research and teaching in the natural sciences. It has a graduate school leading to a degree of doctor of philosophy. It also supports several hundred postdoctoral research investigators as well as a tenured faculty. The George C. Marshall Institute is a not-for-profit study center located in Washington, D.C. It was established in the early 1980s and has been devoted to studies in the public interest related to science and technology, including matters associated with the environment, space science and national defense. It holds frequent question-and-answer discussions around special topics for the benefit of guests from the media and science-related public and private agencies.

I am a past president of the National Academy of Sciences and the American Physical Society. I am also a former Chairman of the Defense Science Board of the Department of Defense and former Science Advisor to the North Atlantic Treaty Organization as well as a recipient of the National Medal of Science and the Vannevar Bush Medal of the National Science Foundation for contributions to science. My undergraduate degrees were in physics and mathematics at Leland Stanford University in California. My doctoral degree was received at Princeton University. During my periods as president, first of the National Academy of Sciences and then of The Rockefeller University, I became broadly conversant with most fields of science. An extended statement of my career is given in the attached material in the form of a curriculum vitae.

Q. What is the purpose of your testimony?

A. My purpose is to offer my observations to the Minnesota Commission concerning the scientific basis for recommendations that public policy bodies should take actions now or in the near future because of a concern that anthropogenic emissions of carbon dioxide and other gases may lead to global climate change. Specifically, I have reviewed the portions of the testimony of Christopher Davis of the Department of Public Service, Peter Ciborowski of the Minnesota Pollution Control Agency and Stephen Bernow on behalf of the Izaak Walton League, et al., that relate to the science behind the global warming hypothesis. I note that this testimony seems to be based in large part on the witness' interpretation of the work of the Intergovernmental Panel on Climate Change. I am concerned that the Commission may misread this testimony and conclude that there is some kind of international scientific consensus that there is a scientifically based need for governments to take immediate strong action to counter the threat of global warming. I note in this regard the testimony of Dr. Bernow recommending that the Minnesota Commission take a "leadership role" and implement policies based on reducing carbon dioxide emissions to 80% or even 50% of current levels.

My testimony is submitted as a part of a "panel" of five scientists on the science of global warming. My testimony will present an overview of the scientific method - how science works to further our understanding of the natural world. I will then discuss the limitations of the greenhouse hypothesis within the context of the scientific method. I will conclude that it cannot be scientifically demonstrated that anthropogenic emissions of carbon dioxide and other gases represent a serious threat to mankind in the foreseeable future.

The other "panel" members are Dr. Richard Lindzen of the Massachusetts Institute of Technology, Dr. Robert Balling of Arizona State University, Dr. Patrick Michaels of the University of Virginia and Keith Idso, a research scientist with the Institute for Biospheric Research at Arizona State University. Dr. Lindzen's testimony will focus primarily on the limitations of the computer simulation models, known as GCMs or General Circulation Models, on which the greenhouse hypothesis is primarily based. Dr. Balling and Dr. Michaels will testify that the greenhouse hypothesis is not supported by actual climatological observations, that is, the predictions of climate change generated by the models are contradicted by phenomena observed in the natural world. They will also testify that the principle climatological consequences of global climate change that concern Messrs. Davis and Ciborowski and Dr. Bernow - such as dramatic sea level rise, increased storminess and major ecological change -are not likely to occur. Finally, Mr. Idso, will present the results of two studies he has conducted showing that increasing atmospheric carbon dioxide levels are likely to produce beneficial effects for plant life.

Q. Please present your testimony.

A. My testimony is submitted in the form of the attached paper. In addition, I am attaching the following publications which I co-authored with two other distinguished scientists for the Marshall Institute entitled Scientific Perspectives on the Greenhouse Problem (1989) (full text and executive summary); Global Warming: What Does the Science Tell Us? (1990); and Global Warming: Recent Scientific Findings (1992).

STATEMENT OF DR. FREDERICK SEITZ
MINNESOTA PUBLIC UTILITIES COMMISSION
MARCH 15, 1995

The dramatic success that scientific research has had in revolutionizing our understanding of the natural world and in advancing almost all forms of technology depends critically on the application of a tightly controlled interplay of speculation and experiment, guided by intuition and logic. Moreover, it is essential for the process that the experiments which lead to conclusions be repeatable, so that they can be rechecked both by the original observers and by others who have a comparable level of expertness. This is usually achieved most easily when the system under study exhibits a fairly direct cause and effect relationship that can be readily demonstrated. Indeed, the art of good experimentation usually involves a struggle to isolate the systems that are under observation in such a way that the coupling between theory and experiment can be made as directly as possible. That is why so much scientific research centers about special purpose laboratories involving equally specialized and controlled equipment. Over the century, good scientists, aware of the degree to which unexpected factors may determine the outcome of an experiment and lead to false results, have learned to become cautious about the way in which they announce the results, hoping either that others will soon confirm them, or that they will find an even more direct way of supporting the conclusions they have drawn. Good scientists tend to have a streak of built-in professional conservatism with regard to going public.

An excellent example of this occurred recently in relation to experiments being carried out at the National Fermi Accelerator Laboratory near Chicago. For several years the scientists there have been looking for a new particle which is predicted to be produced when atoms having a high energy of motion collide. The basis for the search is a promising but still speculative theory. The careful systematic experiments carried out at the Fermi Laboratory seem to indicate reasonably clearly that the predicted particle does indeed exist, yet the group involved, showing characteristic professional caution, hesitated to publish their preliminary results until they felt that they were fully confirmed by additional repetitive experiments. Actually, in this instance, individuals in other laboratories requested that they publish their results, preliminary though they might be, in order that the broader scientific community interested in the field would know the current state of affairs in some degree of detail. The scientists in the Fermi Laboratory complied, but with appropriate statements of reservation in their publication.

This is not to say that within the confines of a meeting with professional peers a scientist will not be outspoken concerning a highly speculative concept he or she would like to be believe is valid but has not yet been proven. This is part of the healthy internal life of the profession. For example, on one occasion several decades ago a great virologist offered, in a highly dramatic manner, the suggestion to colleagues attending a meeting of the National Academy of Sciences that they look for a possible connection between the onset of cancer and the presence of viruses in the cancer cells. This was a purely speculative idea at the time that was offered in order to provide a forum of guidance for cooperative research to experts in the field.

Unfortunately, there are many areas of investigation in which the most ideal form of direct experimentation is not possible because of the intrusion of complexity. This occurs, for example, when the effects being measured are influenced by a variety of concomitant factors and it is humanly impossible to achieve the most desirable form of isolation of the system under study. Such is almost certain to be the case when dealing with large-scale geophysical phenomena, such as those related to the ocean, the atmosphere, and the land masses, in which many factors combine to influence the system being observed. For example, we still do not know for certain what caused the great ice ages of past millennia, although it seems clear that the wobbling of the axis of rotation of the earth may have played a significant role. It is only within recent decades, with the development of high altitude rockets, that we have begun to have a reasonably clear understanding of the origin of the so-called Northern Lights. In fact, there is still much to be learned about them since, among other things, complex events that take place on the surface of the sun play a major role in influencing variability.

During the last century scientists recognized that some gases occurring naturally in the atmosphere, such as water vapor and carbon dioxide, serve as something in the nature of a thermal blanket, preventing incoming solar radiation that is absorbed near the earth's surface from being re-radiated into outer space as infrared radiation. In fact, the amount of such gases that has normally been present in the recent past has been sufficient to raise the temperature near the surface of the earth by about sixty degrees fahrenheit above what it would be without the carbon dioxide. While water vapor is the most important, about ten percent of the warming is attributed to carbon dioxide. Other gases such as methane can play a similar additional role in contributing to the thermal blanket.

Studies of ancient ice such as that in the polar caps show that the amount of carbon dioxide in the atmosphere has varied from period to period so that the warming blanket has had a variable history. It is still an open scientific question concerning the degree to which the earth's temperature in the past and the amount of carbon dioxide present in the atmosphere at a given time correlate with one another - a basic scientific issue.

Once the industrial and domestic use of fossil fuels such as coal, oil, and natural gas began to increase with the growth of modern industry in the last century, several scientists began to wonder if the additional, so-called anthropogenically released carbon dioxide would cause an increase in the average temperature near the surface of the earth and produce additional "global warming," that is, warming in addition to what would occur naturally. This topic was, in fact, brought to focus anew in the 1950s by the famous earth scientist Dr. Roger R. D. Revelle of the

Scripps Institution of Oceanography. He noted not only that the amount of carbon dioxide in the atmosphere was indeed rising, but that the mean temperature of the earth's surface had risen by nearly one degree fahrenheit over the previous century. It should be emphasized that Revelle always believed that it was of primary importance to understand the underlying scientific facts involved in this relationship and exhibited the typical caution of a good scientist. He did not leap to conclusions that would require immediate responses from governments that could have a bearing on the course of our industrial civilization.

At the heart of matters related to the possibility of anthropologically induced warming are two basic questions. First, which came first, the warming or the rise in carbon dioxide observed during the past century; second, will any such rise in the future have serious consequences for mankind, for example, during the next century? Revelle, as a prominent thinker on social and environmental issues, was not at all unmindful of the possibility that serious consequences might result from the accumulation of anthropogenic carbon dioxide in the atmosphere, but also felt strongly that the underlying scientific issues should be understood much more clearly before the scientific community should make any strong recommendations concerning industrial or domestic practices that could have far-reaching, unfavorable economic or social consequences.

Regarding the two questions just mentioned, it should be emphasized that rises and falls in mean global temperature of the order of one or two degrees fahrenheit appear to have been quite common since the end of the last ice age, ten or twelve thousand years ago. Such variations must be regarded to be the result of natural factors, perhaps variations in the output of solar energy. In this connection, Dr. Louis A. Scuderi, studying variations in growth rings in trees which have been preserved over the past two thousand years (see the scientific journal Science, Volume 259, 1433-1436, 1993), noted that the more or less average length of the warming and cooling period has been about one hundred and twenty-five years so that the rise in global temperature that has been observed over the last century could be primarily a result of natural factors in the main. In keeping with this possibility are two important observational facts: first the decade to decade variations in the relatively recent rise of temperature do not match the more steady rise in the use of fossil fuels very closely but do correlate much better with variations in solar activity. Second, the global temperature has remained essentially constant over the past fifteen years or so, as if we may be near the peak of a cycle of rising temperature.

In order to emphasize the complexities of the situation one faces in trying to make decisions concerning possible additional increases in global temperature in the next century, it should be noted that we have incomplete information concerning three basic factors that are involved. These are length of time that carbon dioxide released in the atmosphere remains there before interchanging with what might be called natural temporary storage reservoirs of the gas on land or sea, the degree to which such reservoirs are saturated at present, and the rate at which such temporary reservoirs feed into more long-term, permanent forms of storage of carbon either by physical or biological means. Studies of the fate of the radioactive carbon dioxide produced during open-air tests of nuclear weapons in the 1960s indicate fairly clearly that the exchange of anthropogenic carbon dioxide with that in the first type of reservoir is of the order of five years. Unfortunately we do not have accurate knowledge of the extent to which such reservoirs are saturated or the rate at which the carbon dioxide becomes more permanently bound.

Beyond this, we have only partial knowledge of the relative amounts of atmospheric carbon dioxide produced by biological sources, by volcanoes or by the release from some natural reservoir as a consequence of global warming itself. Both time and intentionally directed scientific research would be required to resolve such issues further. Fortunately the present leveling off in the rise of global temperatures indicates that we do have such extended time available.

It is perhaps understandable that some scientists should be so concerned about the possible effects of additional warming that they are willing to try to short-circuit the time that would be required to resolve such basic issues by what I regard as the traditional methods of science based on careful observations. Some scientists, for example, are attempting to develop computer simulations of processes that could cause changes in global temperatures using the large computers now available. While I admire such heroic efforts, and hope that in the long run they will prove to serve as auxiliary aids in processing experimental data, I cannot regard them as being in any sense a substitute for results obtained by more direct measurements, granting that time is needed for such measurements. The reliability of results which are generated by a computer depends on the reliability of the information fed into it. We clearly need better experimental information than we now have if we are to begin to understand the level of global warming we may expect by the years 2025, 2050, or 2100.

It should be added here that none of the computer simulations carried out thus far have succeeded in giving results which describe with reasonable accuracy the details of the rise in global temperature which we have experienced during the last century or so. This shows that major inputs are lacking in the computer-based methods used at present. How even more unlikely is it that such methods will predict with any reliability what we can expect in the next century with the present level of knowledge.

Some scientists are so deeply concerned about what might be called the possibility of a "worst-case" situation with respect to global warming in the next century that they insist that we should make radical changes in our industrial civilization starting immediately. Such changes would involve substantial shifts in the use of available resources and cause changes in both the course of industrial development and the style of living found in the most advanced industrial countries. Such individuals are apparently unwilling to abide with the pace at which the traditional methods of scientific research can be expected to give us a clearer picture of the nature and magnitude of such a threat. Their activities are carried on through many channels and their recommendations receive much attention from components of the media which enjoy publicizing sensational viewpoints. They have been particularly active in the meetings of the Intergovernmental Panel on Climate Change of the World Meteorological Organization and the United Nations Environmental Program which was created in 1988. This organization held a much publicized major meeting in Brazil in 1992 and continues to issue reports periodically.

The reports of the Intergovernmental Panel on Climate Change are usually prepared in two forms. At base is a large detailed technical report generated by the numerous scientists serving on specialized committees and subcommittees. Associated with it is a much briefer summarizing report prepared by a very selected group of participants. While the larger technical report generally exhibits the traditional forms of reservations regarding the interpretation of scientific information derived from research in complex situations, the summarizing report, which is much more likely to be read by governmental officials and representatives of the media, tends to be based less on the contents of the technical report, with its cautionary statements, and more upon the opinions of the members of the special committee which prepared it. In fact, the summarizing report usually supports the view that immediate action should be taken. This disparity between the two reports has become a source of controversy within the scientific community. For example, the widely read international scientific journal Nature has had several editorials during the past year criticizing the authors of the summarizing reports for mis-using the scientific material made available to them by those working on the basic reports. (See for example Nature, Volume 371, page 269, 1994; Volume 372, page 400, 1994).

It is frequently stated in the press or by individuals in Washington that the views of the scientists who desire to have the international community take immediate and stringent action that would substantially change present-day industrial and domestic practices are characteristic of the great majority of scientists. That is, only a small minority has the opposite opinion and would follow a more traditional scientific approach to the issue of potential global warming before making a decision. I believe that the reverse actually is the case. Most good scientists would like to be far more certain about the factors which influence global warming under existing circumstances before making such a decision. They are no less concerned about the well-being of humanity and the fate of the planet but, like I, believe we have the time to comprehend the trends more fully.

FREDERICK SEITZ

Born	4 July 1911	San Francisco, California
Married	18 May 1935	Elizabeth K. Marshall

Education

Leland Stanford University, A.B. 1932 (Mathematics)
Princeton University, Ph.D. 1934 (Physics)
Princeton University, Proctor Fellow 1934-5

Honorary Doctorates

University of Ghent, Belgium (hon. Causa) 1957
University of Reading, England (D.Sc.) 1960
Rensselaer Polytechnic Institute, Troy, New York (D.Sc.) 1961
University of Notre Dame, Notre Dame, Indiana (LL.D.) 1962
Marquette University, Milwaukee, Wisconsin (D.Sc.) 1963
Carnegie Institute of Technology, Pittsburgh, Pa., (D.Sc.) 1963
Princeton University, Princeton, New Jersey (D.Sc.) 1964
Case Institute of Technology, Cleveland, Ohio (D.Sc.) 1964
Northwestern University, Evanston, Illinois (D.Sc.) 1965
Michigan State University, East Lansing, Michigan (LL.D.) 1966
University of Delaware, Newark, Delaware (D.Sc.) 1966
Lehigh University, Bethlehem, Pennsylvania (LL.D.) 1966
Polytechnic Institute of Brooklyn, Brooklyn, New York (D.Sc.) 1967
University of Michigan, Ann Arbor, Michigan (D.Sc.) 1967
Illinois Institute of Technology, Chicago, Illinois (LL.D.) 1968
University of Utah, Salt Lake City, Utah (D.Sc.) 1968
Brown University, Providence, Rhode Island (D.Sc.) 1968
Duquesne University, Pittsburgh, Pennsylvania (D.Sc.) 1968
Saint Louis University, St. Louis, Missouri (D.Sc.) 1969
New York University, New York, New York (LL.D.) 1969
Nebraska Wesleyan University, Lincoln, Nebraska (D.Sc.) 1970
Davis & Elkins College, Elkins, West Virginia (L.H.D.) 1970
University of Illinois, Urbana, Illinois (D.Sc.) 1981
Universita di Pavia, Pavia, Italy, 1977
University of Port Elizabeth, South Africa, 1979
Rockefeller University, New York, New York (D.Sc.) 1981
University of Rochester, Rochester, New York 1984
University of Pennsylvania, Philadelphia, Pennsylvania 1985
University of Miami, Coral Gables, Florida (D.Sc.) 1989

Awards and Honors

Franklin Medal 1965
Department of Defense Distinguished Service Award 1968
Herbert Hoover medal for Distinguished Service 1968
NASA Distinguished Service Award 1969
National Medal of Science 1973
James Madison Medal 1978
NASA Distinguished Service Award 1979
Amer. Col. of Physicians, Edward R. Loveland Memorial Award 1983
National Science Board, Vannevar Bush Award 1983
Department of Energy Departmental Award for Public Service 1993
University of Illinois, Naming of:
Frederick Seitz Materials Research Laboratory, 1993
Acta Metallurgica J. Herbert Hollomon Award, 1993
Materials Research Society von Hippel Award, 1993

Academic and Professional Positions

1935-1936	University of Rochester	Instructor in Physics
1936-1937	University of Rochester	Assistant Professor of Physics
1937-1939	General Electric Research Labs	Research Physicist
1939-1941	University of Pennsylvania, Randal Morgan Laboratory of Physics	Assistant Professor of Physics
1941-1942	University of Pennsylvania	Associate Professor of Physics
1942-1949	Carnegie Institute of Technology	Professor of Physics, Head of Department
1949-1957	University of Illinois	Research Professor of Physics
1951-1952	University of Illinois	Director of Control Systems Laboratory
1952-1957	University of Illinois	Technical Director of Control Systems Lab.
1957-1964	University of Illinois	Head, Physics Dept.
1962-1965	National Academy of Sciences	President
1964-1965	University of Illinois	Dean of Graduate College and Vice President for Research
1965-1969	National Academy of Sciences	First Full-time President
1968-1978	The Rockefeller University	President
1941-1945	National Defense Research Committee	Civilian Member
1945	War Department	Consultant to Secretary of War
1946-1947	Oak Ridge National Laboratory Clinton Laboratories	Director of Training in Atomic Energy
1959-1960	North Atlantic Treaty Organization	Science Advisor

Board and Committee Memberships, Consultant Activities

1. CORPORATE

Akzona, Incorporated
Director: (1973-1982)

American Machine and Foundry Company
Director: (1961-1966)

Ampex Corporation
Director: (1965-1971)

Charles Stark Draper Laboratory, Inc.
Director: (1978-1982)

Comtex Scientific Corporation
Scientific Advisory Board (Member: 1982-1986)

Image Data Corporation
Director: (1988-1190)

Ogden Corporation
Director: (1977-)
Technology Committee Member: (1987-)
Management Committee Member: (1977-)

Profile Diagnostic Sciences
Director: (1987-), Chairman: (1190-)

RJR Nabisco, Inc. (formerly R.J.Reynolds, Inc.)
Consultant and Member: Medical Research Committee (1978-1988)

2. GOVERNMENT:

Federal: (Agencies and Departments)

a) Air Force
Office of Aerospace Research
Scientific Advisory Group (Member: 1963-1971)

b) Armed Forces
Industrial College of the Armed Forces
Advisory Board (Member: 1961-1965)

c) Commerce
National Bureau of Standards
Statutory Visiting Committee (Member: 1962-1966)

d) Congress
Library of Congress
Liaison Committee for Science and Technology
(Member 1963-1970)

Committee Memberships, Consultant Activities (continued)

e) Defense
  Defense Science Board
    Chairman: (1964-1968)
    Vice Chairman: (1961-1962)
    Member: (1958-1961)
    Member ex-officio: (1968-1969)
    Member-at-large: (1969-1971)
    Member ex-officio: (1985-1990)

  Strategic Defense Initiative Organization Advisory Committee
    Chairman: (1985-1991), Member: (1985-)

f) Energy Research and Development Administration
  Solar energy Research Institute Committee (SERI)
  (Member: 1975-1977)

g) Executive
  Advisory Group on Anticipated Advances in Science and Technology (Member: 1970-1976)

  National Cancer Advisory Board
  (Member: 1972-1974; 1976-1982)

  National Commission on Materials Policy
  (Member: 1971-1973)

  President's Science Advisory Committee
  (Member: 1962-1969)

  Panel on High Energy Accelerators, Joint with General Advisory Committee of the Atomic Energy Commission (Member: 1962-1969)

  President's Committee on the National Medal of Science
  (Chairman: 1962-1963; Member ex-officio: 1966-1969)

h) National Aeronautics and Space Administration (NASA)
  Space Program Advisory council (SPAC)
  (Chairman: 1973-1977)

i) Navy
  Office of Naval Research
  Naval Research Advisory Committee
  (Chairman: 1960-1962
  Member: 1955-1971)

j) Office of Technology Assessment
  Panel on New Ballistic Missile Defense Technology
  (Member: 1985)

k) Selective Service System
  National Selective Service Science Advisory Group
  (Member: 1965-1970)

Committee Memberships, Consultant Activities (continued)

l) Smithsonian Institution
Advisory Council (Member: 1966-1969)

m) State Department
Bureau of Oceans and International Environmental and Scientific Affairs (OES)

ECOSOC Committee on Science and Technology for Development
(Chairman of U.S. Delegation: 1973-1978)

Bureau of Near Eastern and South Asian Affairs
Panel of Advisors (Member: 1966-1969)

UNESCO Monitoring Panel (Member: 1984)
UNESCO Reform Observation Panel (Member: 1985-1988)

State:
Illinois
Science Advisory Council of Illinois
(Chairman: 1964-1967
General Vice chairman: 1967-1968)

New York
Advisory council for the Advancement of Industrial Research and Development (Member: 1971-1975)

INTERNATIONAL
North Atlantic Treaty Organization
Science Advisor (1959-1960)

FOREIGN
India
Ministry of Education
Education Commission of Inquiry
(Consultant: 1964-1966)

Republic of China (Taiwan
Science and Technology Advisory Group to the Premier, Chairman: (1979-)

China Foundation for the Promotion of Education and Culture
Member, Board of Trustees

3. UNIVERSITIES

Associated Universities, Inc.
Brookhaven National Laboratory

Brown University
Visiting Committee (Member: 1975-1977)

Case Institute of Technology - Department of Metallurgy
Visiting Committee (Member: 1964-1968)

<u>Board and Committee Memberships, Consultant Activities</u> (continued)

UNIVERSITIES (continued)

Consortium of Universities of the Washington Metropolitan Area
Board of Trustees (Community Member: 1967-1969)

Georgetown University
Center for Strategic and International Studies
Advisory Board (Member: 1968-1981)
Chairman Advisory Committee (1975-1981)

Harvard University
Board of Overseers of Harvard College
Overseer Physics Visiting Committee (Member: 1963-1969)

Lehigh University
Board of Trustees (Member: 1970-1981)
International Relations Visiting Committee
(Member: 1971-1979, Chairman: 1974-1979)

Oak ridge Associated Universities
Board of Directors (Member: 1969-1971)

Princeton University
Association of Princeton Graduate alumni - Life Member
Alumni Council (Honorary Member: 1968-)
Board of Trustees - Graduate School Alumni Trustee
(Member: 1968-1972)
Department of Physics Advisory Council
(Associate Member: 1968-1971; 1981-1986)
Woodrow Wilson School
Rockefeller Public Service Awards
Selection Committee (Member: 1967-1975)
Annual Giving Committee (Member: 1969-1972)

Rockefeller University
Board of Trustees (Member: 1966-1978)
President (July 1968-1978)

Southwest Center for Advances Studies
Board of Trustees (Member: 1963-1969)

Stanford Research Institute
Council (Member: 1971-1977)

University of California
Miller Institute of Basic Research
Advisory Board Member (Member: 1958-1964)

University of Chicago
Argonne National Laboratory - changed to Argonne Universities Association 1965
*Policy Advisory Board (Member: 1958-1966)
Physical Metallurgy and Solid State Review Committee
Ex-officio member
Solid State Science Division (Consultant: -1965)

Board and Committee Memberships, Consultant Activities (continued)

University of Illinois
Physics Department: Research Professor (1949-1965)
(July 1965 - granted full time leave as Professor of Physics.
August 1968 - severed connections)
Graduate College: Dean (1964-1965)
Center for Advanced Study: Advisor (1968-)
Vice President for Research (1964-65)
Beckman Institute: External Advisory Committee
(Member: 1987-)

University of Miami at Coral Gables
Center for Theoretical Studies
(Member: Scientific Council 1977-)
School of Engineering and Architecture
(Member: Visiting Committee 1983-)

University of Nevada System
Desert Research Institute
National Advisory Board (Member: 1975-1979)

University of Pennsylvania
Board of Overseers for the Faculty of Arts and Sciences
(Member: 1976-1979)
Natural Science Association - Board of Advisors
(Member: 1986-)

University of Puerto Rico - Puerto Rico Nuclear Center (PRNC)
Advisory Committee of Scientists (Member: 1967-1970)

University of Texas
Medical Branch at Galveston
Advisory Committee for the Marine Biomedical Institute
(Member: 1975-1978)

4. INTERNATIONAL AND FOREIGN ORGANIZATIONS

Belgian American Educational Foundation, Inc.
(Member and Trustee 1975-)

International Council of Scientific Unions
Committee on Science and Technology in Developing Countries
(Member: 1966-1969)

International Union of Pure and Applied Physics
Vice President (1960-1966)
United States National Committee
(Member-at-large: 1968
Chairman: 1961-1967
American Physical Society Representative: -1974)

Royal Society of Arts
Benjamin Franklin Fellow: (Member-at-large: 1968-1970)

5. ACADEMIES ABROAD

Academy of Rumanian Peoples Republic
Physics Section (Honorary Member: 1965-)

Akademie de Natur Wissenschafter, Goettingen, Germany
(Corresponding Member: 1962-)

Deutsche Akademie de Naturforscher Leopoldina, Halle, Germany
(Member: 1964-)

"Ettore Majorana" Centre for Scientific Culture, Erice, Sicily

Foreign Member of the Finnish Academy of Science and Letters
(elected 1974)

L'Academie Suisse des Sciences, Basel, Switzerland
(Honorary Member: 1966-)

World Academy of Art and Science
(Fellow: 1962- lifetime membership)

Institutions and Associations

Accuracy in Media, Inc.
National Advisory Board (Member: 1972-)

American Academy of Achievement
Executive Committee (Member: 1966-1968)
Golden Plate Award Recipient 1966

American Academy of Arts and Sciences (Fellow: elected 1962)

American Association of University Professors

American Crystallographic Association

American Foreign Service Association
(Associate Member: 1967-1969)

American Institute of Mining, Metallurgical and
Petroleum Engineer, Inc. (elected 1939)

American Institute of Physics
Governing Board (Chairman: 1954-1959)
Member: Elected by American Physical Society
1960-1969
Committee on Physics and Society (Chairman: 1970-1973)
Long Range PLanning Committee (Chairman: 1972-1974)
Council of the Friends of the Center for History of Physics
(Member: 1975-)

American Museum of Natural History
Centennial Committee (Member: 1969-1970)
Trustee (1975-)

American Philosophical Society (Member: 1949-)
Committee on Research (Member: 1972-1975)
Committee on Membership, Class I, Mathematical and
Physical Sciences (Member: 1972-1973)
Committee on Development (Member: 1982-1985)

American Physical Society
(President: 1961)
Council Member: Representative on American Institute of
Physics Governing Board - see AIP
Representative on U.S. National Committee for the International
Union of Pure and Applied Physics: 1961-1974

American Society for Engineering Education

Argonne Universities Association - see Universities Policy
Advisory Board (Member: 1965-1967)

Aspen Institute for Humanistic Studies - (Member: 1967-1969)

Association of American University Presses, Inc.
Advisory Council (Member: 1964-1965)

Atlantic Legal Foundation, Board of Advisors, Member: (1991-)

Institutions and Associations (continued)

Bohemian Club - Special Faculty Member (1966-   )

The Callier Center for Communication Disorders
Trustee: 1976-1978)

Century Association - Resident Member (1970-   )

Commission on Independent Colleges and Universities (CICU)
Graduate Programs Committee (Chairman: 1975-1976)

Committee for and Effective UNESCO
Executive Board (Member: 1976)

Committee to Maintain a Prudent Defense Policy
(Member: 1969-   )

Commonwealth Fund Book Program
Advisory Board (Member: 1982-   )

Cosmos Club

Education & World Affairs
Board of Trustees (Member: 1963-1968)

Franklin Institute - Journal See PUBLICATIONS

George C. Marshall Institute
Chairman, Board of Directors (1984-   )

John Simon Guggenheim Memorial Foundation
Educational Advisory Board (Member: 1965-1969)
Special Advisor on Fellowship Applications
Chairman of the Board of Trustees (1976-1983)
Nominating Committee (Member: 1974-1983)

Hudson Institute
Prospects for Mankind Project Advisory Board
(Member: 1975-1976)

Institute for Defense Analyses (IDA) - Sponsoring Member:
Representative of University of Illinois (1964-1965)
Board of Trustees (Member: 1964-1965, 1970-   )
Executive Committee (Member: 1970-   )

Institute for the Future
Permanent Trustee of the Corporation (Elected 1968)
Executive Committee (Member: 1971-1974)

Institute of International Education (IIE)
Board of Trustees (Member: 1971-1978)

International Club of Washington (1964-1969)

International Health Resource Consortium
Vice Chairman of the Board (1977-1979)

L.S.B. Leakey Foundation (Founding Board Member: 1968)

Institutions and Associations (continued)

Link Foundation, Technical Assistance Board (Member: 1982-)

Richard Lounsbery Foundation, Bd. Memb. (1980-), President (1993-)

Manpower Institute - Board of trustees (Member: 1969-1979)

Memorial Sloan-Kettering Cancer Center
Advisory Board (Member: 1969-1983)
(Vice Chairman of the Board: 1978-1983)
Committee on Scientific Policy
Trustee (1969-1983)
Board of Overseers Member (1983-)

Midwest Science Advisory Committee (Chairman: 1965-1968)

Midwestern Universities Research Association (Board Member)

Mount Wilson Observatory, Board of Advisors, (1991-)

National Academy of Engineering
U.S. Civil Aviation Manufacturing Industry Panel
(Chairman: 1983-1985)

National Academy of Sciences - Member (elected 1951)
President: (July 1962-June 1969)
Member of the Joint Committee for the Sino-American Program
of Scientific Cooperation (1976-1978)
Editor, Five Year Outlook II, Science and Technology (1980-1981)

National Council on Radiation Protection and Measurements (NCRP)
Member: 1970-)

National Research Council
Office of Physical Sciences, Assembly of Mathematical and
Physical Sciences
Advisory Board (Member: 1975-1977)
Board on Chemical Sciences and Technology
Commission on Physical Sciences, Mathematics and Resources
Chairman, Major Materials Facilities Committee - 1984
Co-Chairman, Planning Panel for Large International Science
& Technology Facilities (1985-1986)
Board on Science and Technology for International Development
Commission on International Relations (Member 1981-)
Committee on Research Grants (Chairman: 1981-1988)
Panel on Reassessment of A-Bomb Dosimetry
(Chairman: 1982-1987)

National Science Foundation
Alan T. Waterman Award Committee (Member: 1977-1980)

National Space Association
Board of Governors (1975-)

New York Academy of Sciences
Editorial Board (Member: 1983-)
Science Policy Association (Steering Committee: 1985-)

Institutions and Associations (continued)

Nutrition Foundation
Board of Trustees (Member of Corporation: 1964-1985)
Board of Directors
Executive Committee (Member: 1972-1985)
Special Review Committee (Member: 1968-1969)
Nominating Committee (Member: 1982-)

Optical Society of America

Pacific Science Center Foundation, Board of Trustees 1962

Phi Beta Kappa, Phi Beta Kappa Associates (Elected 1969)

Polytechnic Institute of Brooklyn - Policy Planning Board (Member: 1971-1974)

Research Corporation
Board of Directors (Member: 1966-1982)
Executive Committee (Member: 1970-1982)

Rockefeller Foundation
Board of Trustees (Member: 1964-1977)
Executive committee (Alternate: 1964-1965)
(Member: 1966-1977)
Nominating Committee (Member: 1966-1967)
(Chairman: 1967-1968)

Rockefeller University
President: July 1968 - June 1978
Board of Trustees (Member: 1966-1978)

Science Service
Committee on Development (Member: 1969-1974)
Board of Trustees (Member: 1971-1974)

Sigma Xi
Committee on the Common Wealth Awards Program
Vice Chairman: (1981)
Member: (1981-1986)

Sloan-Kettering Institute for Cancer Research
Chairman of the Board (1978-1983)

Society of Naval Architects & Marine Engineers
Special Member 1965

Teller Foundation, Board of Advisors, Member: (1991-)

Texas Instruments Incorporated
Board of Directors (Member: 1971-1982)

United Aircraft Corporation
Board of Directors (Member: 1969-1971)

Universal Movement of Scientific Responsibility
Board of Directors (Member: 1975-1980)

Institutions and Associations (continued)

Universities Research Association, Inc. (URA)
Chairman of the Council of Presidents 1974
Vice President (1965-1969)
Executive Committee (Member: 1965-1969)

Universities Space Research Association, Inc. (USRA)
Council (Chairman): 1971, 1972
Vice Chairman: 1969-1970)
Board of Trustees and Executive Committee
(Ex-officio Member: 1971-1978)
Lunar Science Institute - Member

University Corporation for Atmospheric Research (UCAR)
Trustee (1975-1982)

Volunteers for International Technical Assistance (VITA)
Advisory Council (Member: 1964-1966)
Board of Directors (Member: 1965-1973)

Washington Academy of Sciences: Fellow (Elected 1967)

Washington Center for Metropolitan Studies
Board of Trustees (Member: 1962-1968)

Woods Hole Oceanographic Institution (WHOI)
Member of the Corporation
Department of Physical Oceanography
Scientific Visiting Committee (Member: 1968-1978)

Woodrow Wilson National Fellowship Foundation
Trustee: (1972-1982)
Chairman: (1974-1982)

Publishing Affiliations

Academic Press (Reorganized 1968 as public corporation merging Academic Press, Inc., Academic Press, Inc - London Ltd. and Johnson Reprint Corporation - acquired by Harcourt, Brace and Janovich, Inc. in 1970)

Solid State Physics Series: Co-editor

American Institute of Physics
On The Frontier, My Life in Science, 1994, Author

Association of American University Presses, Inc.
See: Institutions and Associations

Bulletin of Atomic Scientists
Educational Foundation for Nuclear Sciences, Inc. - Member

Die Umschau in Wissenschaft und Technik
Editorial Board (Member: 1964-)

Franklin Institute
Journal: Associate Editor (1939)-1942)

Il Nuovo Ciomento
Editorial Board - Member

Industrial Research
Editorial Advisory Board (Member: 1964-1970)

McGraw-Hill Book Company
Encyclopedia of Science and Technology
Consulting Editor in Solid State PHysics (1955-1983)
The Modern Theory of Solids (1940) - author
The Physics of Metals (1943) - author

Physica Status Solidi
Editorial Board (Member: 1966-)

Springer-Verlag
The Science Matrix: The Journey, Travails, Triumphs - (1991) author

John Wiley & Sons
Preparation and Characteristics of Solid Luminescent Materials - Co-editor (1948)

WFA Ex.___, (FS-3)

SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

EXECUTIVE SUMMARY

George C. Marshall Institute
Washington, D.C.

SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

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The George C. Marshall Institute provides technical
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with a major public policy impact.

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Second Printing

WFA Ex. ___, (FS-4)

SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

George C. Marshall Institute
Washington, D.C.

PRINCIPAL FINDINGS

- Current forecasts of the man-made greenhouse effect do not appear to be sufficiently accurate to be used as a basis for sound national policy decisions.
- Forecasters cannot rely on the temperature increase observed in the last 100 years as an indicator of greenhouse warming in the next century.
- Policy makers would be wise to invest in the additional resources needed to improve the reliability of greenhouse forecasts before undertaking corrective programs that could turn out to be unnecessary — or even undesirable if a natural cooling occurs in the 21st century.
- The total cost of supercomputing facilities for the major climate forecasting groups would be no more than $100 million. The investment would be cost-effective when viewed in the perspective of the large and potentially negative impact on the five-trillion-dollar U.S. economy, that could result from a premature decision based on inaccurate and possibly misleading forecasts.
- The reliability of the greenhouse forecasts also suffers from gaps in observations of clouds and oceans, and a poor understanding of processes vital to the determination of climate, such as moist convection. A stronger effort in global observations is as important as the provision of computing power.
- Augmentation of the pitifully small force of scientists attempting to make progress on this important problem is as vital as improved observations and computing power.
- Certainty will never be achieved in a matter as complex as the forecasting of climate for the coming century. However, it is our judgment that if a prudent investment is made in computing power, observing programs and added manpower, answers that have a usable degree of reliability can be provided for policy makers within 3 to 5 years. Through such an invest ment, the government can accelerate the pace of climate research to yield the necessary information in years rather than decades, so that timely action can be taken if needed.

(iii) IMPROVING THE FORECASTS

The third focus of the study was measures for diminishing the gross uncertainties in the current greenhouse forecasts. Procurement of top-line supercomputers for the major climate forecasting groups could significantly diminish the level of uncertainty in the greenhouse forecasts by improving the treatment of ocean currents — one of the major unknowns in the present forecasts.

The increased detail achievable with more powerful computers would also lead to information on regional climate changes — in particular, the occurrence of regional droughts — which cannot be predicted with any useful degree of accuracy by the crude models currently in use.

Computing power is one major requirement for better climate predictions. Another need, equally important, is for more observations of the actual conditions prevailing on the earth and in its oceans and atmosphere, and for monitoring of factors causing climate change, such as greenhouse gas concentrations, values of the "solar constant" and changes in the transparency of the atmosphere caused by volcanic eruptions.

Observations of the oceans are particularly important because the state of observational knowledge of the oceans is much poorer than that of the atmosphere. More complete data on the variation with depth of ocean temperature, salinity and currents are badly needed.

More complete observations and better physics are also needed for the problem of cloud feedback. As noted, attempts by several groups to deal with the effect of cloud feedback on the greenhouse forecasts yield results that differ by as much as 300 percent. There are grounds for optimism that these large cloud-generated uncertainties can be reduced if more information is acquired on the types of clouds, and cloud heights, that arise under different conditions. Collecting this information should be a top-priority objective in greenhouse research in the next few years.

However, observations and number-crunching power alone will not suffice to resolve the difficult public policy issues posed by the poor reliability of current forecasts. Added scientific manpower is also needed. Fewer than 50 atmospheric scientists are working on greenhouse and climate forecasts in the entire U.S. The size of this group is entirely inadequate for the importance of the task these scientists are being asked to perform.

end of the range of current estimates — 1 °C or less — would only offset the natural cooling, leaving the world's temperature in the 21st century within a degree or so of its present level.

(ii) CAUSES OF FORECAST UNCERTAINTY

The second focus of the study was the cause or causes of the large uncertainty in the current greenhouse forecasts. Among the known causes of uncertainty, the most important one is the effect of clouds — in particular, cloud feedback, i.e., the way in which the cloud cover changes in response to the initial stages of the greenhouse warming. The extent of this feedback is perhaps the largest single unknown in the greenhouse forecasts. After cloud feedback, next most important among the known causes of uncertainty in the predictions is the effect of ocean currents.

Clouds. Most of the wide variation in the current greenhouse forecasts is traceable to differences in the treatment of clouds. Clouds tend to cool the earth by screening it from the sun's rays; at the same time, they tend to warm the earth by blocking the outward flow of heat to space. These warming and cooling effects are roughly 10 times bigger than the man-made greenhouse effect projected for the next century.

When the earth starts to heat up in the first stages of greenhouse warming, there is a shift in the balance of the heating and cooling effects of clouds. The shift is very hard to determine, because we are trying to calculate small man-made changes within large natural climate factors. Does the balance of cloud effects shift in a direction that amplifies the greenhouse warming, or cuts it down? This is the cloud feedback problem. Different groups get answers that differ by 300% on cloud feedback. As noted, this is the largest single source of uncertainty in the forecasts.

Oceans. Oceans also play an important role in the greenhouse effect, because they absorb and store large amounts of heat. Consequently, the greenhouse forecasts are strongly affected by the ocean currents which carry huge volumes of water and heat from one part of the globe to another. In one representative case, the calculations showed that when ocean currents are included, the global warming is decreased by 1 °C — a significant decrease.

In particular, the Antarctic Ocean hardly warms at all, and may cool slightly. This diminishes the probability of a breakup of the West Antarctic ice sheet, accompanied by a rise of sea levels and flooding of coastal cities all over the world.

Allowance for the oceans requires more observations of ocean currents and temperatures, more scientific manpower — and an enormous increase in computing power. The need for more computing power relates to the fact that at the present time, because of the length of the computations, the forecasters break up the earth into large areas, up to 500 miles across. This crude approximation of the earth's surface is required in order to complete the calculations in a reasonable time. But the Gulf Stream, which controls the climate of Western Europe, is less than 100 miles wide at some points. A 100-year forecast that takes a few months now with 500-mile areas, would take *decades* if the computation were done with 100-mile areas so as to include ocean currents properly. Yet including the effect of ocean currents is essential.

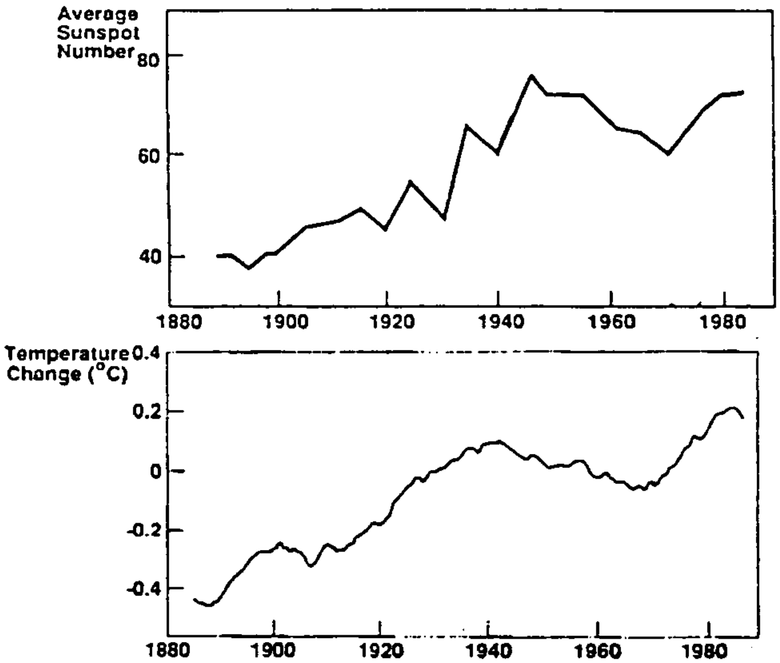
Poor Quality of Regional Forecasts. Useful greenhouse forecasts have to predict not only global temperature trends, but also regional changes — e.g., not just the Northern Hemisphere, but agricultural areas in California or the Midwest. These regional climate changes can be very different from global trends. For example, in the 1970s and 1980s, when the world as a whole became substantially warmer, England and Northern Europe became substantially colder.

Current greenhouse forecasts do extremely poorly on regional forecasts. In fact, different scientific groups sometimes arrive at contradictory results for the same region. In the U.S., in forecasts for three important regions — California, the southeast, and the Great Lakes — some greenhouse forecast groups predict substantial ***decreases*** in summer rainfall as a result of the greenhouse effect, while others predict substantial ***increases***.

0.5°C temperature increase observed on the earth in the last 100 years.

Evidence in support of solar variability as a significant factor is provided by the charts below, which reveal that the changes in the earth's temperature have followed changes in solar activity over the last 100 years. The charts below show that when solar activity increased from the 1880s to the 1940s, global temperatures increased; when solar activity declined from the 1940s to the 1960s, temperatures also declined; when solar activity and sunspot numbers reversed and started to move up again in the 1970s and 1980s, temperatures did the same.

These correlations seem to explain the features that are so puzzling when scientists try to interpret the observed temperatures as



Comparison of (a) 33-year running average of sunspot numbers and (b) average global temperatures from 1885 to 1985.

a consequence of the greenhouse effect. The evidence points to changes in the sun's brightness as one contributor to the global warming observed since 1880.

The objection is sometimes raised to this explanation, that the changes actually measured in the sun's brightness thus far amount to only 0.1%, which is too small to have a significant climate impact. In fact, calculations show that a change of 0.3% to 0.5% in the sun's brightness is needed to account for the temperature changes observed since 1880.

However, if the brightness of the sun can change by 0.1% during one particular period of observation, it is plausible that larger changes can occur at other times or over longer intervals of time. As noted, recent observations show that stars identical to the sun in their properties can change in brightness by as much as 0.4% over several years — enough to account for all the recent temperature changes observed on the earth.

These facts indicate that a large part of the 0.5°C warming of the earth in the last 100 years may be the result of a combination of natural variability and solar variability. In fact, these non-greenhouse factors could account for nearly all the temperature rise, with the greenhouse effect contributing a negligible amount.

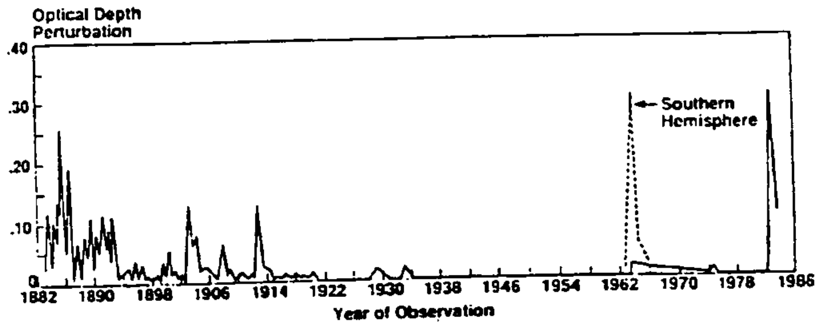
The effect of the wild cards introduced into the greenhouse studies by natural and solar variability is that no conclusion about the magnitude of the greenhouse effect in the next century can be drawn from the 0.5°C warming that has occurred in the last 100 years.

Evidence for recurring cold spells. The climate record contains another trend that may be useful in forecasting the climate for the 21st century. According to records for the last 800 years, cold spells have occurred in Northern Europe every few hundred years — in the 13th, 15th, 17th and 19th centuries. The most famous of these is the Little Ice Age of the 17th century, when Northern European temperatures were about 1°C below today's levels. According to these trends, another cold spell is due in the 21st century, with cooling of as much as 1°C. A greenhouse effect at the lower

OTHER FACTORS CAUSING TEMPERATURE CHANGES

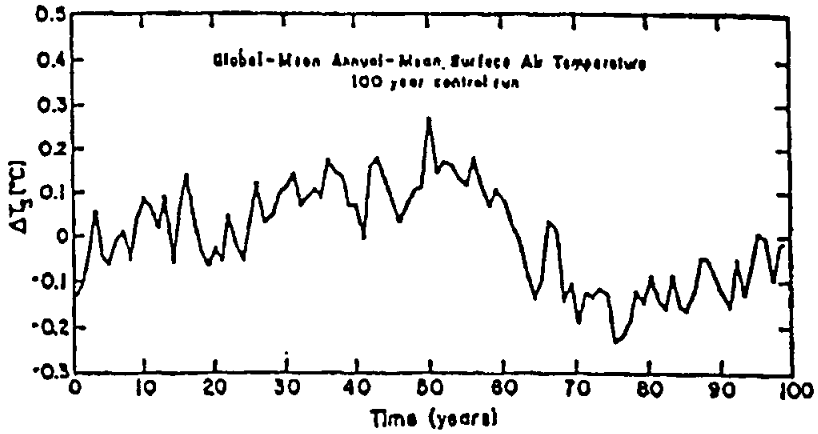
These departures from the calculated greenhouse temperature curve suggest that other forces besides the greenhouse effect have been influencing the earth's climate in recent decades. What forces could be changing global temperatures?

Volcanoes. Volcanic eruptions are one possibility because they create a layer of particles that reduces the transparency of the atmosphere. Thus, by screening the earth from the sun, volcanoes have a cooling effect. In fact, volcanoes have been suggested as the cause for the substantial temperature drop between 1940 and 1970. However, the observations of the transparency of the atmosphere shown in the chart below, which reflect the occurrence of volcanic eruptions, indicate no appreciable reduction in transparency in the 1940-1970 period. Volcanoes influence the climate at times, but cannot account for the observed temperature decrease between 1940 and 1970.



Observed changes in the transparency of the atmosphere, based on changes in the apparent brightness of non-varying stars. Two major volcanic eruptions of recent years — Mt. Agung in 1963 and El Chichon in 1982 — show up clearly as strong peaks. Very little volcanic obscuration of the atmosphere was observed in the 1940s and 1950s, contradicting the view that volcanoes caused the dip in temperatures commencing in the 1940s.

Natural Variability. Another possible explanation for the temperature changes in the last 100 years is the natural variability of the earth's climate — changes in climate that occur without any obvious cause, i.e., no change in carbon dioxide, volcanic eruptions, or any other known factor in climate change. Dr. Hansen did a trial 100-year computer run, shown on the chart below, that revealed a substantial natural variability of climate. He found that it is possible for the earth's temperature to change by as much as 0.4°C over 25 years as a result of natural climate variability — nearly enough to account for the observed 0.5°C change over the last 100 years.



A 100-year computer run of global mean temperature. In addition to year-to-year fluctuations of about 0.1° C, the calculations show a 0.4° C drop over 25 years without known or obvious cause. This trend appears to be the product of a natural climate variability.

Solar Variability. Finally, satellite measurements show that the sun's brightness can change over time. The measured change was only 0.1%, but astronomical measurements on other stars identical to the sun show changes of up to 0.4% over a period of years — big enough, if they occurred on the sun, to account for the entire

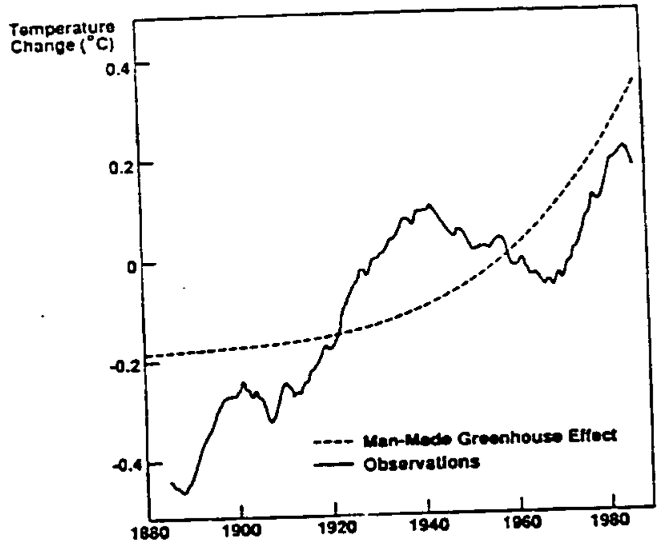
KEY ISSUES

In view of the importance of these questions of reliability in the greenhouse forecasts, the study focused on three key issues — (i) How reliable is the 0.5°C warming to date, as a guide to temperature increases in the next century? (ii) What is the cause of the very large uncertainty in the greenhouse forecasts? (iii) What can be done to make the greenhouse forecasts more accurate and useful to policy makers?

(i) SIGNIFICANCE OF THE RECENT 0.5°C WARMING

First, how reliable is the 0.5°C warming, as an indicator of the full greenhouse effect projected for the next century?

The chart below compares observed temperatures in the last



Comparison between observed global average temperature and calculations based on the greenhouse effect. The dashed line indicates the calculated temperature increase caused by the greenhouse effect since 1880. The solid line indicates the observed temperatures for the same period. Both curves show a 0.5°C rise over the 100-year interval. However, the observed temperatures, unlike the greenhouse curve, show a rapid rise in the first 50 years, followed by a decrease from 1940 to 1970.

100 years with calculations by Hansen et al., on the temperature increase produced by the man-made greenhouse effect in the same period. Both the observations and the greenhouse calculations show an increase of about 0.5°C. As noted earlier, these greenhouse calculations, which yield a 0.5°C rise for the last 100 years, also predict a 3°C greenhouse rise in the next century. The agreement between the two curves suggests that a 3°C rise is a reliable estimate for the greenhouse temperature increase that will occur in the 21st century.

However, the comparison of the two curves also shows substantial differences:

First, most of the observed rise of 0.5°C occurred in the first 50 years, from 1880 to 1930. But less than a third of the total carbon dioxide increase occurred in that early period. Although greenhouse calculations explain the total increase in global temperature up to 1980, it is not possible for the greenhouse effect to explain the rapid rise in temperature between 1880 and 1930.

Second, from the 1940s to the 1970s, while greenhouse gases continued to build up in the atmosphere, the observed temperatures ***decreased*** substantially. The decrease was large enough to have a significant agricultural impact on Northern Europe. No sign of this drop in temperature from the 1940s to 1970s appears in the greenhouse forecast for the same period.

The fall in temperature between 1940 and 1970 is particularly difficult to explain as a greenhouse phenomenon, because this entire period was one of strong economic growth and increasing emission of greenhouse gases, and should have been a period of accelerating temperature rise. Even if allowance is made for a delayed response to the increase in the greenhouse gases, the 1940-1970 period should have been one of increasing temperatures — provided the greenhouse effect was actually the main driver of climate change in that period.

INTRODUCTION

This extract from the full report summarizes the scientific issues underlying the accuracy and reliability of current forecasts of the greenhouse effect. The analysis is based on information provided by James Hansen of NASA, Syukuro Manabe of NOAA, T.M.L. Wigley of the University of East Anglia and others who briefed Institute scientists and spent time with them in subsequent lengthy discussions.

The following facts provided the context for the study:

First, the temperature of the earth's surface apparently has increased by 0.5°C over the last 100 years. We judge this temperature increase to be real, although its existence has been disputed by some experts. The observations of the temperature increase are supported by recent reports of a rise in sea level of 1 ft. over the last 100 years, which is roughly what would be expected for a 0.5°C rise in temperature.

Second, several scientific groups have calculated the temperature increase expected as a result of increased atmospheric concentrations of carbon dioxide and other greenhouse gases produced by human activity. The results obtained by these groups range from 1°C to 5°C, or 2°F to 9°F, for the greenhouse warming expected by the mid-to-late 21st century.

The high end of the range of forecasts — a warming of 5°C — is potentially very damaging, with possible impact including severe dust bowl conditions and a major increase of sea level, flooding low-lying coastal areas in the U.S. and around the globe. The low end of the estimates —a man-made greenhouse warming of 1°C — would be far less serious, and might be canceled by a natural cooling expected for the next century on the basis of past trends.

Because of the wide spread in the predicted size of the greenhouse effect for the next century — ranging from small to catastrophic — some scientists have suggested that we look at the 0.5°C warming that has occurred thus far, as a better guide to what can be expected in the future. According to this reasoning, if the greenhouse effect were intrinsically very small we would not have seen a rise as great as the 0.5°C that has been observed in the past 100 years. On the other hand, if the greenhouse effect were extremely large, we would have seen a larger temperature increase than the 0.5°C that has actually been observed thus far.

Extending this line of reasoning, we can ask — What greenhouse calculations just reproduce the 0.5°C rise that has been observed to date, and what temperature increase do these particular calculations predict for the next century?

The answer is that the best calculations — i.e., those that best reproduce the 0.5°C warming observed in the last 100 years — predict a temperature increase of 3°C in the mid-to-late 21st century.

This is a significant conclusion. A 3°C temperature increase, while not as catastrophic as the 5°C increase predicted by some groups, would still have a major and destructive impact on the world's climate.

SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

EXECUTIVE SUMMARY

CONTENTS

PREFACE

This report is based on the technical literature relating to the climatic impact of increased greenhouse emissions and on discussions with several scientists actively involved in the technical problems of long-range climate forecasting. We are indebted to James Hansen of the NASA Goddard Institute for Space Studies for a highly informative briefing, and also to Albert Arking and Kenneth Schatten of the NASA Goddard Space Flight Center, T.M.L. Wigley of the Climate Research Unit of the University of East Anglia, Syukuro Manabe of the NOAA Geophysical Fluid Dynamics Laboratory, Robert D. Cess of the State University of New York at Stony Brook, Sabatino Sofia of Yale University, Charles P. Sonett of the University of Arizona and Michael Rampino of New York University.

We are particularly grateful to Drs. Manabe, Wigley, Arking and Rampino for extensive and enlightening discussions subsequent to the formal briefings.

We also profited greatly from very interesting discussions with Robert Malone of Los Alamos Laboratory, Stephan Schneider, John Eddy and George C. Reid of the NOAA Aeronomy Laboratory, Gerald A. Meehl of the National Center for Atmospheric Research, Richard Lindzen of MIT, Michael McElroy of Harvard University and Wilmot Hess of the Department of Energy.

Finally, we wish to thank Sally Baliunas of Harvard University and Simon Worden of the U.S. Air Force for alerting us to the fact that stars with properties nearly identical to those of the sun have been observed to undergo variations of several tenths of a percent in luminousity, large enough to be climatically significant. We are also indebted to Wes Lockwood of Lowell Observatory for transmitting to us the results of a recent observational program revealing variations of up to 0.4% in the luminosity of sun-like stars.

Frederick Seitz, *Chairman*
Robert Jastrow
William A. Nierenberg

SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

I. THE GREENHOUSE PROBLEM

This study considers the technical issues involved in forecasting the intensity of the greenhouse effect — a warming of the earth produced by the presence of carbon dioxide and certain other gases in the atmosphere. These gases absorb heat that would otherwise escape into space, returning some of it to the earth's surface and raising the temperature on the planet. The gases that have this heat-absorbing property are called greenhouse gases, and their warming influence on the earth is called the greenhouse effect.

The focus of the study is the evidence for a significant rise in the temperature of the earth in the last 100 years, coincident with a substantial increase in the amount of carbon dioxide and other greenhouse gases in the atmosphere. The increased atmospheric concentration of these gases is apparently the result of human activities, such as the burning of coal and oil.

Several scientific groups have concluded that man-made 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 as a result of the burning of fossil fuels and other human activities, the average temperature of the earth may rise in the 21st century by as much as 5° C, or 9° F. Such an increase might cause widespread drought in many agricultural areas and have a destructive impact on human life in many parts of the world.

Not all experts in the field of climate studies agree with these conclusions. However, a substantial body of scientific opinion considers the man-made greenhouse effect to be a serious concern that must be addressed.

IS THE GREENHOUSE EFFECT A NEW PHENOMENON?

The potentially harmful greenhouse effect resulting from human activities is a relatively small addition to a large, natural greenhouse effect that has warmed the earth for billions of years. This natural greenhouse effect — which is, of course, unrelated to human activity — comes largely from water vapor in the earth's atmosphere. Water vapor, like carbon dioxide, is a greenhouse gas; it partly blocks the return flow of heat coming up from the surface and atmosphere to space thereby warming the earth. Naturally occurring carbon dioxide in the atmosphere adds to the greenhouse warming produced by the water vapor, but its effect is much less than that of water vapor.

The greenhouse effect produced by water vapor and other gases occurring naturally in the earth's atmosphere has been highly beneficial to life on our planet. If it were not for this natural greenhouse effect, the average temperature on earth would be a chilly 0° F — well below freezing. The warming effect of the earth's greenhouse gases has raised the average global temperature by 60° F — from 0° F to 60° F. Sixty degrees Fahrenheit is a comfortable temperature as an average over the planet. In fact, it may be close to the optimum average temperature the earth could have, from the viewpoint of supporting life over the largest possible area of the globe.

REASONS FOR ADVOCATING PROMPT GOVERNMENT ACTION

The enhanced greenhouse warming produced by human activity will be no more than a few degrees, and quite small compared to the 60-degree natural greenhouse effect, but its consequences could be devastating in the short term. A temperature increase of up to 5° C could lead to recurrent and severe summer drought in the midwestern states of the U.S. and other productive agricultural regions. Although opinion is divided on the matter, in the worst-case scenario a warming of 5° C might also break up the West Antarctic ice sheet, eventually, after several centuries, raising sea levels by as much as 15 feet. Large areas of New York City, Miami and other coastal cities and densely populated river deltas would be submerged, and the lives of hundreds of millions of individuals living in coastal areas all over the world would be disrupted.

Government officials in the U.S. and other countries have begun to address the need for major policy decisions dictated by these grim projections. Their concern is heightened by the fact that the warming caused by the greenhouse effect takes a long time to build up and may not be noticeable for several decades, but once it has developed, it may take centuries to eliminate. As a consequence, if corrective actions, such as cutting down on the burning of fossil fuels, are delayed until the full measure of the greenhouse warming is upon us, it may not be possible to ameliorate its destructive effects for many generations.

II. RELIABILITY OF THE PREDICTIONS

How accurate are the greenhouse forecasts? The basic statement that carbon dioxide and other greenhouse gases warm a planet is not in doubt. Venus, for example, has an enormous amount of carbon dioxide in its atmosphere — 60,000 times more than the earth — and the surface of Venus is also oven-hot, with an average temperature greater than 800 degrees Fahrenheit. A calculation of the greenhouse effect produced by the dense concentration of carbon dioxide on Venus indicates that this effect can explain the searing Venus temperatures. No other explanation known to planetary science is adequate to account for these high temperatures.

Mars also has carbon dioxide in its atmosphere; in fact, the Martian atmosphere, although relatively thin, is composed almost entirely of this greenhouse gas. As in the case of Venus, calculations of the greenhouse effect on Mars show that it is warmer by just about the amount that would be expected as a consequence of the carbon dioxide in its atmosphere.

Applying these results to the earth, we can be confident that an increase in the amount of carbon dioxide in the earth's atmosphere must raise the planet's temperature. But by how much? Scientists trying to forecast the amount of greenhouse warming resulting from the increase in man-made carbon dioxide face the problem that the man-made 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 man-made effect accurately, they must be able to compute the natural changes in the earth's climate with great precision. When they attempt to do a precise calculation, they run into two difficulties — oceans and clouds.

INFLUENCE OF OCEANS ON FORECAST ACCURACY

Scientists forecasting the magnitude of the man-made greenhouse effect have found that their results are affected by the ocean currents which carry large volumes of water from one part of the globe to another. When the effect of these large-scale ocean currents is included in the calculations, the size of the greenhouse warming may be decreased.

In one representative case, in which the emission of greenhouse gases was assumed to increase at the equivalent rate of one percent a year (usually regarded as a realistic projection), the calculations showed that if the effect of ocean currents is not included, the entire globe warms up by roughly 2° C to 3° C over the course of the next 50 years. But when ocean currents are included, the northern hemisphere warms up by the same amount as before, but the southern hemisphere warms up by only 1° C.* The Antarctic Ocean hardly warms at all, and may cool slightly.**

The improvement in forecast accuracy resulting from the inclusion of ocean currents thus has an important practical consequence. It diminishes the probability of an eventual breakup of the West Antarctic ice sheet, accompanied by a rise of sea levels and flooding of coastal cities all over the world.

A possible breakup of the West Antarctic ice sheet with a consequent substantial rise of sea levels, although not expected for centuries and indeed a matter of dispute among the experts, is nonetheless among the most menacing potential consequences of the man-made greenhouse warming. Full allowance for the effect of ocean currents in the forecasts may remove this threat from the list of greenhouse dangers.

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* Eventually, the southern oceans must also heat up in response to the increased greenhouse effect, but this will probably take hundreds of years.

** S. Manabe, private communication.

INFLUENCE OF CLOUDS ON FORECASTS

Clouds are the second major problem area for the greenhouse forecaster. Clouds cover roughly half the area of the earth 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 flow of heat to space from the earth's surface. However, recent satellite measurements have shown that this heating effect is outweighed by the cooling effect of the clouds.

Clouds create a problem for the greenhouse forecaster because the natural cooling effect they produce is ten times as large as the entire man-made greenhouse warming projected for the middle of the next century. Their heating effect — which is a natural greenhouse effect — is also considerably larger than the predicted size of the man-made greenhouse effect.

This means that a small change in the earth's cloud cover and cloud heights can greatly change the actual greenhouse warming. Suppose, for example, that because of the greenhouse warming, more water evaporates into the atmosphere from the warmer oceans. That could mean that more clouds would form. But the increased cloud cover would cool the earth, partly offsetting the greenhouse warming. This would be an example of "negative feedback": the greenhouse warming produces more cloud cover; the increased cloud cover feeds back into the climate, and decreases the amount of the greenhouse warming.

On the other hand, suppose that fewer clouds form because, although the atmosphere has more water vapor, the warm air has a lower relative humidity. Consequently, the vapor is less likely to condense into cloud droplets. That would mean a decrease in cloud cover and, therefore, more sunlight reaching the earth's surface and warming the planet. In other words, a change in cloud cover produced by the greenhouse effect would itself enhance or magnify the effect. This would be a case of "positive feedback."

Because the effect of the clouds is roughly 10 times as large as the greenhouse effect predicted for the mid-21st century, a small change in the cloud cover could either diminish the greenhouse warming by a large amount, or magnify it by a large amount, depending on whether the cloud feedback was negative or positive. But small changes in cloud cover are very hard to predict. Consequently, the cloud feedback is also very hard to predict with any accuracy.

Types of clouds and cloud heights are also very important for estimating cloud feedback, and again very difficult to predict with accuracy. The relatively low-altitude stratus clouds block incoming sunlight more effectively than they trap the outgoing heat from below, and hence tend to have a cooling effect. Higher-altitude, tenuous cirrus clouds, on the other hand, let more light through, but block the flow of heat from below, and tend to have a warming effect.

Most greenhouse forecasts show that the cloud feedback is positive. That is, the combined effect of changes in cloud cover and cloud height or cloud type, in response to a greenhouse warming, is to increase the amount of the warming.* But again, by how much? The scientific groups working on the problem differ by 300 percent in their estimates of the amount of extra greenhouse warming produced directly or indirectly by clouds. Some groups say the extra warming is small, while others say it is several degrees.

The practical consequences of these disagreements are very great. They constitute a large part of the difference between forecasts of up to 5°C of temperature increase in the mid-to-late 21st

* The studies show that fewer clouds are formed as a result of the warming because warm air has a lower relative humidity; thus, more sunlight penetrates, the earth is warmed, and the greenhouse effect is magnified. In addition, the clouds that do form tend to do so at higher altitudes. Since at the higher altitudes the cloud tops are colder, they radiate less heat to space, further increasing the greenhouse warming

century, and forecasts of a temperature increase of only 1 °C.

The disagreement arises because the formation of clouds is a complex phenomenon. The different types of clouds — cirrus, cumulus, and so on — absorb heat from below differently, and reflect sunlight differently. Each scientific group working on the greenhouse problem has its own way of handling these complications, and arrives at a different answer.

POOR QUALITY OF REGIONAL FORECASTS

It is important for greenhouse forecasts to be able to predict not only the worldwide temperature trends, but also the climate changes in a region, such as western Europe or the U.S. midwest. Regional climate changes can be very different from the global climate trends. For example, an analysis of temperature records reveals that in the 1970s and 1980s, when the world as a whole became warmer, England and Europe became somewhat colder.

Unfortunately, the greenhouse forecast models do very poorly in attempts to calculate regional climates, even when the region is as large as a continent. One climate forecast used in greenhouse studies predicts, for example, that the July prevailing winds over Western Europe are easterlies, coming from the Eurasian land mass. Actually, these winds are known to be westerlies coming mainly from the Atlantic Ocean. This remarkable mis-prediction has major consequences for the climate of Europe, since, inter alia, winds from the ocean carry more moisture, and cause more rainfall, than winds blowing off the continent.

EFFECT OF AVERAGING OVER LARGE AREAS

When the computations leading to the greenhouse forecasts are carried out, it is assumed at the outset that the surface of the earth can be divided into a number of small areas. Within each area, the temperature of the surface is represented by a single number, which is supposed to be the average temperature for that area. The humidity, cloud cover, height above sea level, and all other quantities affecting the climate also are represented each by one number for the area, which is supposed to be their average value for that area. This is done to diminish the amount of computing required for the forecast.

The trouble with this process of averaging over areas is that the "small" areas assumed in the greenhouse forecasts are not so small. In most forecasts used for the greenhouse problem, the areas used to describe conditions at mid-latitudes — in the U.S., and Europe, for example — are about 500 miles in extent.*

In the U.S., an area 500 miles across nearly spans the distance between Los Angeles and Albuquerque. Two such adjacent areas encompass the territory running from the Mexican border to Canada.

When areas used for averaging are as large as this, two completely different climate zones — for example, desert and fertile farmland — can exist within a single area. But an "average" over desert and fertile terrain would yield a forecast useless to the inhabitants of either region.

Averages over large areas also reduce the climate impact of mountain ranges, which can be very great. A mountain range deflects the flow of air and often causes moisture to precipitate as rain. As a result, the windward side of the range is generally wetter than the leeward side. But when the average height above sea level is computed for an area, the mountains are spread out and flattened, often to the point of insignificance.

A forecast based on such mountain-flattening averages would predict little difference in climate between heavily forested Ore-

* They are chosen to be that large because the computers available to climate forecasting groups do not have the speed and power needed to generate a more detailed forecast in a reasonable amount of time.

gon and the Nevada desert, because it would miss the effect of the Sierra and Cascade mountain ranges in dumping moisture from the Pacific on the west coast.

Most experts on climate forecasting agree that the computations used for current greenhouse forecasts have little or no capability for regional prediction. One demonstration of that inadequacy can be seen in the fact that two independent greenhouse forecasts, yielding the same global temperature rise in response to greenhouse gas increases, can give contradictory regional forecasts.

COMPUTING DIFFICULTIES IN GENERATING ACCURATE FORECASTS

If the inclusion of ocean currents changes the greenhouse forecasts so markedly, why do most scientific studies of the greenhouse effect continue to ignore the effect of these currents? If averaging over large distances leads to inaccurate regional forecasts, why do greenhouse forecasters not average over smaller distances?

The reason is that averaging over smaller distances costs the forecaster very heavily in computing time. The amount of computing time required for a greenhouse forecast goes up sharply when the forecaster attempts to describe the earth and its atmosphere and oceans in more detail by breaking the globe up into small areas.

For example, if the forecasts are averaged over 250-mile areas instead of 500-mile areas, the computation takes eight times as long. A single 100-year forecast takes approximately 4 months when the areas are 500 miles across. If they were reduced to 250-mile areas, the forecast would take nearly three years.

These computing difficulties are exacerbated by the problem of the oceans. Exceedingly high resolution is required for an adequate treatment of ocean currents. The Gulf Stream, for example, which has such an important effect on the climate of northern Europe, is less than 100 miles wide at its narrowest point. Describing such currents means dividing the ocean's surface into many areas, each no more than 100 miles across.

The oceans make up three-quarters of the area of the globe. An enormous amount of computing time would be required to generate a forecast with a description of the oceans as detailed as this. For example, if the size of the areas over which the currents are averaged is merely cut in half, the calculations become 16 times longer.*

If all the important questions about the greenhouse warming could be answered by two or three 100-year forecasts, the answers everyone is waiting for might be obtained in a reasonably short time — even though each forecast takes years — by dividing the workload among several computing groups.

But if the greenhouse forecasts are to make a useful input to policy decisions they must be repeated a large number of times, to determine how the greenhouse warming depends on different assumptions regarding such factors as the rate of consumption of coal and oil, increase in electrical power use and third-world economic growth. A great many computing runs are needed to answer these basic questions. With the limited computing power currently available to climate forecasters, decades would be needed to provide policy makers with the information they require.

Yet greater accuracy and reliability in the forecasts are essential, in spite of the heavy computing burden and lengthy computations that will entail. The forecasts do not appear to be good enough in their present form to provide a sound basis for decisions affecting the economies of the U.S. and other nations.

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* Normally, doubling the detail (and halving the area of averaging) leads to an eight-fold increase in computing time. The additional factor of two in this case comes from the fact that as the area over which the Gulf Stream is averaged diminishes, the velocity of the Gulf Stream increases proportionally.

IMPORTANCE OF ADDITIONAL COMPUTING POWER

Inadequate allowance for the effect of changes in ocean circulation is a major source of uncertainty in the greenhouse forecasts. The inability to generate meaningful regional forecasts is another reason why these forecasts are not of much practical value at present, even for the limited purpose of sounding an alarm over the coming greenhouse warming.

Both problems would be ameliorated if the surface of the earth were broken up into considerably smaller areas — at the expense of a substantial increase in computing time.

As noted above, increased computing power will be helpful in meeting the need for more accurate forecasts. Computing power alone will not solve the problem of the regional forecasts, but it will enable the greenhouse forecast groups to represent mountains more accurately, and they will also be able to start experimenting with other changes needed to tune up the regional forecast capability of their climate models. At present, the greenhouse forecasters — forced to resort to averaging over areas that may span a quarter of a continent — cannot even make a start on that problem.

The bottom line is that greenhouse forecasts could be made both more accurate and more timely — and, therefore more useful to policy makers — 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. These supercomputers can diminish errors and uncertainties in the forecasts resulting from inadequate allowance for the effect of ocean currents. They will also allow greenhouse forecasters to make a serious attempt at accurate regional forecasts — an achievement not within their grasp at present.

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. Their computing facilities are underpowered for the importance of the work being done. One hundred million dollars would purchase top-line supercomputer 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.

NEED FOR MORE OBSERVATIONS AND BETTER PHYSICS

Computing power is one major requirement for better climate predictions. The other need, equally important, is for more observations of the actual conditions prevailing on the earth and in its oceans and atmosphere, and for monitoring of factors causing climate change, such as greenhouse gas concentrations, values of the "solar constant" and changes in the transparency of the atmosphere caused by volcanic eruptions.

Observations of the oceans are particularly important because the state of observational knowledge of the oceans is much poorer than that of the atmosphere. More complete data on the variation with depth of ocean temperature, salinity and currents are badly needed.

Moist Convection. These expanded programs for observing clouds, ocean currents and temperatures, and other climate-related properties are vital to the success of the climate forecasting effort. For example, how is heat carried from the ground up to space? Any calculation of global temperature increases due to carbon dioxide emissions must have a fairly accurate answer to that question. Yet the answer is not known very well.

What happens in a general way is that water evaporates from the earth's surface — mainly from the oceans — to form warm, moist air. The warm air expands and rises, carrying its warmth and moisture to higher altitudes.

As the air rises, it cools and condenses into water droplets, and cumulus clouds form. The condensation of the water vapor into droplets of liquid water releases additional heat to the atmosphere. Eventually, the droplets collect into rain drops which fall to the surface, cycling the moisture back to the surface of the earth. However, the heat that was carried up stays in the atmosphere.

This process by which heat and moisture are transported to higher levels in the atmosphere is called "moist convection." Moist convection has an indirect but critically important consequence for the greenhouse effect. By carrying moisture to higher altitudes in the atmosphere, it leads to the formation of clouds. These clouds change the surface temperature because, as noted on page 7, they screen the earth from incoming sunlight, cooling the surface; but they also block the upward flow of heat to space, warming the surface. No one is certain what the net balance of heating and cooling is for the clouds created by moist convection.

Furthermore, when the earth begins to get warmer in the first stages of the greenhouse effect, both the process of moist convection and the clouds it generates are affected, and the balance of the heating and warming is shifted. Is the shift in the direction of more warming, which means the long-term greenhouse warming is increased? Or is it in the direction of cooling, which means the long-term greenhouse warming is cut down?

These uncertainties in the size of the 21st-century greenhouse warming, which are associated with the complexities of moist convection, are only a part of the cloud problem. Clouds are formed in other ways than by moist convection, and each mechanism of cloud formation introduces its own uncertainties into the greenhouse forecasts. As noted earlier, attempts by several groups to deal with the effect of clouds on the greenhouse forecasts yield results that differ by as much as 300 percent.

There are some grounds for optimism that these cloud-generated uncertainties would be reduced if more information could be acquired on the types of clouds, and cloud heights, that arise under different conditions. Collecting this information should be a top-priority objective in greenhouse research in the next few years.

III. CURRENT STATUS OF THE GREENHOUSE FORECASTS

Several greenhouse forecasting groups have estimated the amount of warming that would result if the equivalent concentration* of carbon dioxide in the atmosphere were to double as a result of human activity — a condition that may be encountered in 30 to 50 years. As noted previously, their results for the long-term or "equilibrium" increase in the average temperature of the earth range from a lower limit of 1° C to an upper limit of 5° C, or roughly 2° F to 9° F.** This wide spread in the forecasts made by the different groups is mainly the result of differences in their treatment of clouds.

A greenhouse warming of 1° C — at the lower end of the predictions — could be partly or largely offset by natural climate changes unrelated to human activity. The natural cooling that occurred during the Little Ice Age of the 16th and 17th centuries represented a temperature drop of roughly 1° C relative to today's temperatures. If a natural cooling comparable to the Little Ice Age were to return in the next century, a greenhouse warming of 1° C would have the beneficial effect of ameliorating its destructive impact, leaving global temperatures within a degree or so of their present levels.

On the other hand, an eventual greenhouse warming of 5° C — at the upper end of the range of predictions — would lead to cat-

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* In addition to carbon dioxide, the greenhouse gases include methane, nitrous oxide, and chlorofluorocarbons. For simplicity, all are lumped with carbon dioxide and stated as an equivalent carbon dioxide concentration — i.e., equivalent in their impact on the climate.

** S.H. Schneider, *Science* 243, 771 (1989).

astrophic changes over large areas of the globe in the next century. These changes would be too large to be offset by any likely change in climate due to natural causes. Policy makers surely would undertake early action to forestall this development, if they were confident in the accuracy of the forecasts predicting the large effects.

It may be possible to achieve an accuracy that would warrant this confidence by the application of a heavier concentration of computing power, combined with global observations on the earth's clouds and oceans. At the present time, the greenhouse forecasts tell us only that a serious problem may exist — or it may not.

COMPARISON BETWEEN GREENHOUSE FORECASTS AND OBSERVED TEMPERATURE INCREASES

As noted, while the greenhouse forecasts point to the likelihood of a global warming, they cannot predict its size with confidence. However, the fact that the earth has already become appreciably warmer in the last 100 years apparently indicates that the greenhouse effect is already here, and that its size is substantial.

Carbon dioxide in the atmosphere has increased by about 25 percent since the Industrial Revolution, as the result of the burning of coal and oil, deforestation and other human activities. If the middle range of greenhouse forecasts is correct, this increase in carbon dioxide should have produced a temperature increase of roughly 0.5° C between 1880 and 1985. The temperature measurements show an increase in average global temperature by just the predicted amount of 0.5° C.

The comparison between the calculated greenhouse temperature rise and observed temperatures is shown in Figure 1. The solid line in Figure 1 shows the global temperature change observed on land between 1880 and 1985, averaged over 5-year intervals, as compiled by Hansen and Lebedeff. The observed temperature increases by about 0.5° C between 1880 and 1985, as mentioned in

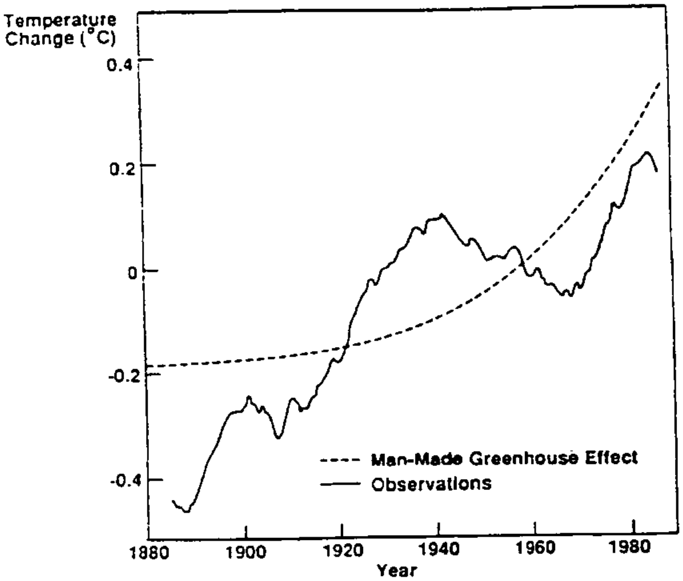

Figure 1. Comparison between observed global average temperature and calculations based on the greenhouse effect. The dashed line indicates the calculated temperature increase caused by the greenhouse effect since 1880. The solid line indicates the observed temperatures for the same period. Both curves show a 0.5°C rise over the 100-year interval. However, the observed temperatures, unlike the greenhouse curve, show a rapid rise in the first 50 years followed by a decrease from 1940-1970.

the previous paragraph.

Similar results have been obtained by Jones and Wigley for land and ocean surface measurements combined, and by Folland and Parker from ocean surface measurements.*

The dashed line in Figure 1 shows the predicted greenhouse

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* Some experts have expressed skepticism regarding the reality of the 0.5°C rise in global temperature. Independent confirmation of the rise comes from recently reported findings that the sea level has risen by roughly one foot in the last 100 years. (W.R. Peltier and A.M. Tushingham, *Science*, 244, 806, 1989.) Calculations indicate that a sea level rise of just about this magnitude should accompany a temperature increase of 0.5°C. However, the authors of the report on the rise of sea level are careful to caution that their findings, while consistent with a 0.5°C global temperature increase, tell nothing about the cause of the increase.

warming during the same period. This curve is obtained from a calculation lying in the middle range of greenhouse forecasts, yielding a mid-to-late 21st century greenhouse warming of roughly 3° C. As noted above, the dashed line also indicates a greenhouse temperature increase of about 0.5°C between 1880 and 1985.

EVIDENCE FOR A SUBSTANTIAL GREENHOUSE EFFECT

Several scientists interested in the greenhouse problem have remarked that the agreement between observations and the greenhouse predictions up to 1985 yields valuable information about the size of the long-time greenhouse warming expected for the 21st century. They point out that if the long-term greenhouse warming in the next century were going to be very much larger than the current estimates suggest, we would have seen a temperature increase of substantially more than 0.5° C between 1880 and 1985.

On the other hand, if the long-term greenhouse effect were going to be substantially less than the low end of the range of greenhouse estimates, the green house effect for the 1880-1985 period would not have produced the 0.5° C warming that has actually been observed in that period.

Some climate experts have concluded that the observed warming of 0.5° C tells us the middle range of greenhouse forecasts — a temperature rise of roughly 3° C in the mid-to-late 21st century — is roughly correct and should be a trustworthy guide to the full greenhouse warming that will occur in the 21st century.

IV. OTHER FACTORS INFLUENCING CLIMATE IN THE LAST 100 YEARS

A closer look at Figure 1, however, raises doubts about the accuracy of the greenhouse forecasts as a predictor of conditions in the 21st century. While the overall temperature increase in the greenhouse forecast agrees with the observed temperature increase of 0.5° C, the shape of the calculated greenhouse curve differs from the observations in important respects.

The greenhouse forecast (Figure 1, dashed line) shows a smooth increase in temperature with time, rising slowly at first and then more rapidly in recent decades. On the other hand, the observed temperatures (Figure 1, solid line) rose from the 1880s to around 1940. Then, although the concentration of man-made greenhouse gases in the atmosphere was now growing rapidly, the observed values dropped substantially between the 1940s and the 1970s.

Two aspects of this comparison seem significant. First, most of the observed rise of 0.5° C occurred in the first 50 years from 1880 to 1930, although less than a third of the total carbon dioxide increase occurred in that period. Second, no sign of the post-1940 drop in temperature appears in the greenhouse forecast for the period from 1940 to 1970, although this decrease was large enough to have a significant agricultural impact on Northern Europe.

The fall in temperature between 1940 and 1970 is particularly difficult to explain as a greenhouse phenomenon, because this entire period was one of strong economic growth and increasing emission of greenhouse gases. Even if allowance is made for a delayed response of the climate to the increased concentration of these greenhouse gases, the 1940-1970 period should have been one of increasing temperatures — provided the greenhouse effect was actually the main driver of climate change in that period.

These departures from the calculated greenhouse temperature curve suggest that other forces besides the greenhouse effect have been influencing the earth's climate in recent decades..

VOLCANIC ERUPTIONS

What kinds of non-greenhouse forces could have been working on the earth's climate in the last 100 years? Volcanic eruptions are one possibility. Erupting volcanoes sometimes emit copious amounts of the gas sulfur dioxide, which become droplets of sulfuric acid in the atmosphere. The sulfuric acid droplets create a global haze that shields the earth's surface from the sun and cools the planet.

The global cooling produced by large eruptions can be substantial, of the order of several tenths of a degree. However, the particles that cause the cooling disappear from the atmosphere in a year or two, so that the climatic impact of even the largest eruptions is relatively brief.

Some experts say that many small volcanoes, erupting in succession in the 1940s and 1950s, could have caused a sustained temperature drop that would explain the post-1940s cooling. However, measurements of changes in the transparency of the atmosphere, shown in Figure 2 (p. 21), do not reveal any effect of this kind from 1914 to 1962. The atmosphere over that entire period was quite clear.*

Several volcanic eruptions did occur in the 1950s, but did not produce a global or hemispheric reduction in transparency and a consequent cooling effect. In some cases this was so because the eruptions were at high latitudes and their product did not enter

* M. Rampino and S. Self, private communication.

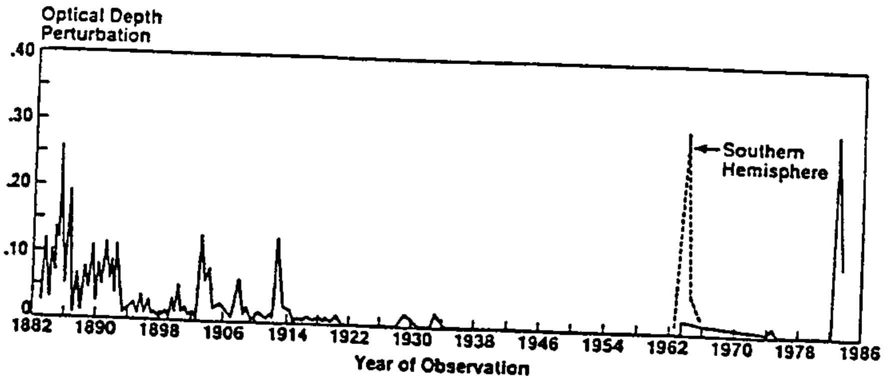

Figure 2. Observed changes in the transparency of the atmosphere, based on changes in the apparent brightness of non-varying stars. Two major volcanic eruptions of recent years — Mt. Agung in 1963 and El Chichon in 1982 — show up clearly as strong peaks. Very little volcanic obscuration of the atmosphere was observed in the 1940s and 1950s, contradicting the view that volcanoes caused the dip in temperatures commencing in the 1940s.

the mid-latitude circulation of the atmosphere. In two other cases — the large eruptions in Iceland in 1947 and Kamchatka in 1956 -- the eruptions not only were at high latitudes, but also produced relatively little sulphur dioxide, and so for two reasons did not add appreciably to the global haze of sulphuric acid droplets.

NATURAL VARIABILITY OF CLIMATE

The natural variability of the earth's climate is another possible explanation for the 0.5° C rise in temperature since 1880. Climate computations suggest that the earth's climate can undergo large swings in temperature that may last for several decades, and have no apparent cause. That is, the computed global temperature may vary by large amounts over decades, even if the computations hold constant the level of volcanic eruptions, concentration of greenhouse gases, changes in the sun's brightness and all other factors that would normally lead to a change in global cli-

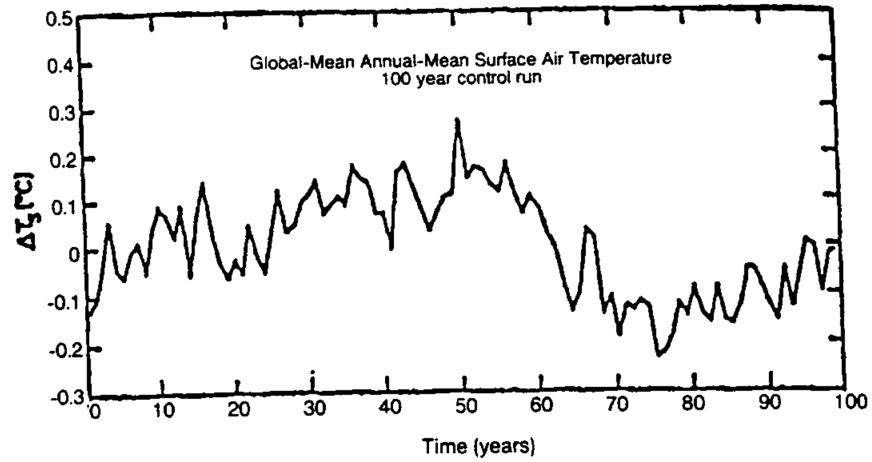

Figure 3. A 100-year computer run of global mean temperature. In addition to year-to-year fluctuations of about 0.1° C, the calculations show a 0.4° C drop over 25 years without known or obvious cause. This trend appears to be the product of a natural climate variability.

mate. This phenomenon of large and seemingly spontaneous changes in climate is known as the "natural variability" of the earth's climate.

Figure 3 shows the result of a 100-year computing run by Hansen et al., in which natural climate variability produced a significant change of roughly 0.4° C in temperature over 25 years, without any change in the so-called "forcing" terms, i.e., no changes in carbon dioxide concentration, solar energy output, volcanic activity or any other external agent.

Although the natural variation in this case happened to be a temperature drop rather than a rise, the implication in these results is that at other times the natural variability of climate might also produce a rise of 0.4° C; or even 0.5° C, over a comparable period.

It is important to note again that such variations in climate apparently can occur naturally, without any change in carbon dioxide concentration or other external "forcing" factors. Figure 3 is evidence that much or all of the 0.5° C rise in temperature observed between 1880 and 1930 may be the product of natural variability rather than the greenhouse effect.

CHANGES IN THE SUN'S BRIGHTNESS

An increase in the sun's brightness is still another possible cause of the 0.5° C increase in temperature observed over the last 100-odd years. Climate calculations indicate that a temperature increase of 0.5° C could be produced by an increase of 0.3 to 0.5 percent in the sun's brightness.* Is it possible that the sun has grown brighter by 0.3 to 0.5 percent since 1880?

This idea that the sun's brightness could vary over intervals as short as years or decades has not been fashionable among astronomers and climate experts. However, recent findings in space science and astronomy have confirmed that such variations do occur. The possibility of solar energy changes on relatively short time scales, which was viewed until recently as an ad hoc conjecture without observational support, is now, because of these findings, an established astrophysical fact.

OBSERVATIONAL CONFIRMATION OF SOLAR CHANGES

The first of the new findings comes from satellite measurements of the sun's brightness, which can be made much more accurately than is possible from the ground. These measurements of the so-called "solar constant" — the amount of solar power per unit area reaching the earth — have revealed a decrease of about

* T.M.L. Wigley, *Secular Solar And Geomagnetic Variations In The Last 10,000 years*, (Stephenson and Wolfendale, eds.), 209 (1988)

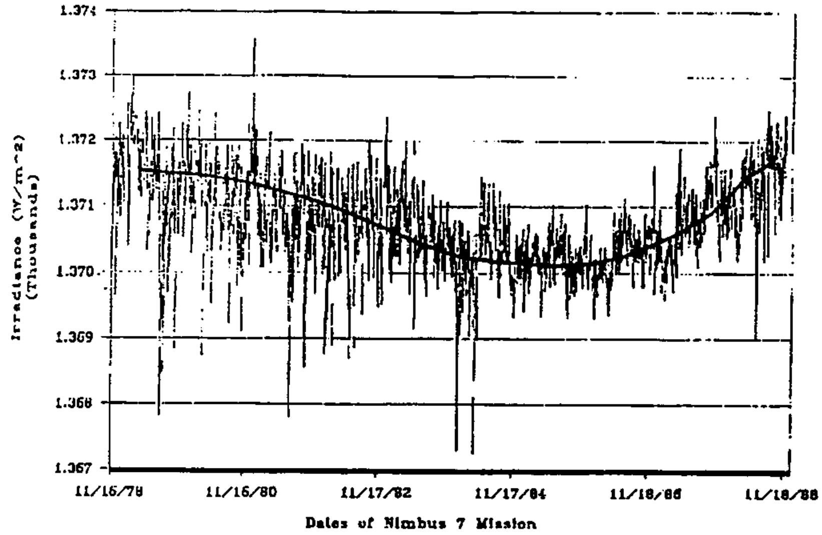

Figure 4. Changes in the solar constant between 1978 and 1988.

0.1 percent between 1978 and 1985, followed by an increase from 1985 to 1988.

Figure 4 shows the measured values of the changes in the solar constant between 1978 and 1988.

The satellite measurements prove that the sun's brightness does, in fact, change from year to year. It is now established that even on time scales as short as years or decades, the solar "constant" is not constant.

The measurements also show that the changes in the solar constant seem to follow changes in the number of sunspots observed during the sunspot cycle. When sunspots are most numerous on the face of the sun, the sun's brightness is greatest; when the sunspots decrease in number, the output of solar energy also decreases.

The measured change of 0.1 percent in the sun's brightness is not large enough to explain such changes of climate as the 0.5° C warming that occurred after 1880. As noted, that would require an increase of 0.3 to 0.5 percent in the solar constant. However, if a 0.1

percent change in solar energy output occurred in this one period of observation, it is possible that changes in the sun's output as large as 0.5 percent or more may occur at other times, or over longer periods of time.

Recent astronomical observations of stars have confirmed that such substantial changes in energy output do, in fact, occur in many stars similar to the sun. In a study of 36 such stars, Lockwood and Skiff found that nearly half varied by more than 0.5 percent in brightness over an interval of a little less than four years.*

Four among the varying stars were solar twins, almost identical to the sun in age, mass and other properties. Two of the four solar twins remained roughly constant over the four-year period, and the other two varied in brightness by 0.23 percent and 0.42 percent, respectively. Figure 5 shows the variation in brightness from year to year observed in the latter two stars.

Baliunas and Vaughan have found that one of the two variable stars also displays an eight-year cycle of surface activity similar to the sun's 11-year sunspot cycle (Figure 6).* Comparison of Figure 6

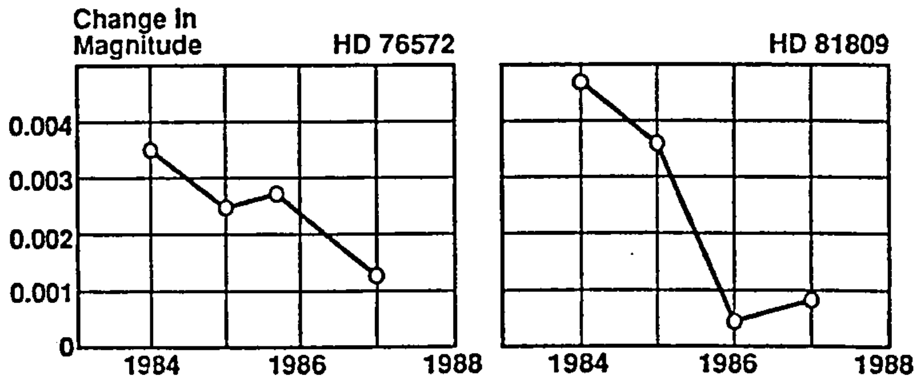

Figure 5. Changes of 0.23 percent (left) and 0.42 percent (right) in the brightness of two stars with nearly identical properties to those of the sun, over a four-year period.

* G.W. Lockwood and B.A. Skiff (Lowell Observatory), Air Force Geophysics Laboratory, Report AFGL-TR-88-0221 (1988)

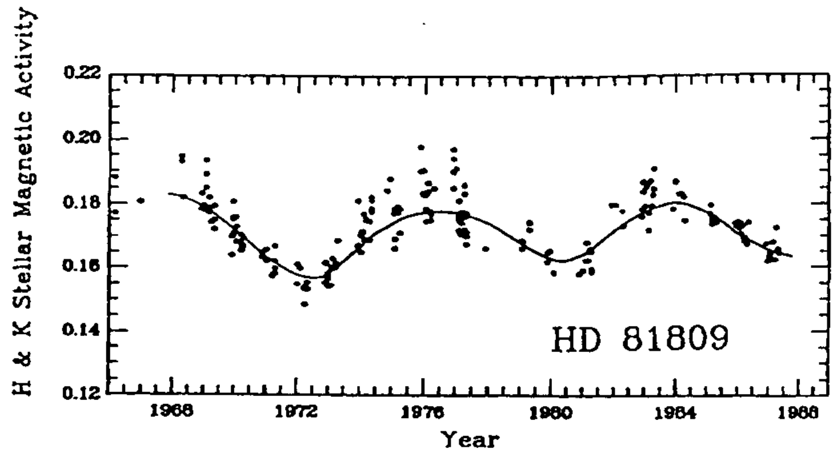

Figure 6. An 8-year cycle of changes in surface activity in HD 81809.

with Figure 5 reveals that, as in the case of the sun, when this star's surface activity declines, its brightness also decreases.

CHANGES IN SOLAR BRIGHTNESS AS A FACTOR IN CLIMATE CHANGE

Is the 0.5° C warming in the last 100 years the consequence of a man-made greenhouse effect?

As noted on page 19, the temperatures observed since 1880 have a pattern of change that does not resemble the temperature curve calculated from the man-made greenhouse effect. However, they do resemble the changes in solar activity for the same period.

Figure 7 compares the changes in solar activity — represented by average sunspot numbers — to the changes in global temperature from 1885 to 1985. When solar activity increased between the 1880s and the 1940s, global temperatures also increased. When solar activity declined between roughly 1940 and the 1960s, temperatures also declined. When solar activity and sunspot numbers re-

* S. Baliunas and A. Vaughan, *Ann. Rev. Astron. Astrophys.* 23, 379 (1985)

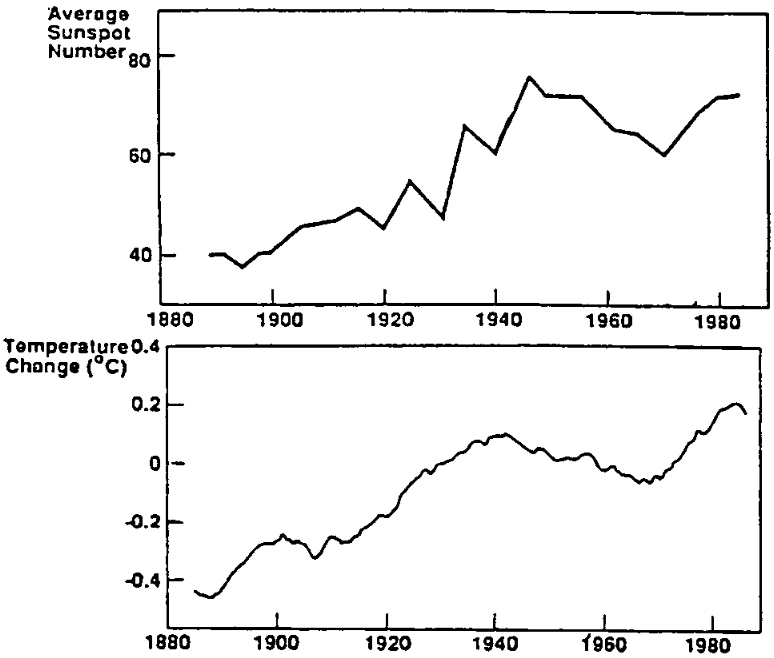

Figure 7. Comparison of (a) 33-year running average of sunspot numbers and (b) average global temperatures from 1885 to 1985.

versed and started to move up again, temperatures did the same.

These parallel patterns of change could be a coincidence, but they suggest a solar explanation for at least a part of the post-1880 temperature rise.

IMPLICATIONS FOR THE MAGNITUDE OF THE GREENHOUSE EFFECT

These findings on the climate impact of natural and solar variability have significant implications for policy makers considering today how to cope with the catastrophic greenhouse temperature increase predicted for the mid-21st century.

As indicated earlier, because of the wide spread in the predictions of greenhouse warming, and the difficulty in deciding which prediction is most accurate, scientists concerned with offering sound advice on the greenhouse problem have tended to rely on the observed temperature increase of 0.5° C since 1880 as their best evidence that the greenhouse effect is already here, and that steps should be taken now to cope with its full development in the next century.*

As noted on page 18, a greenhouse effect big enough to explain the post-1880 temperature rise of 0.5° C will probably produce a temperature increase of about 3° C in the mid-to-late 21st century. A temperature increase of this magnitude would be sufficiently serious to warrant consideration of early action by policy makers.

On the other hand, if some cause other than the greenhouse effect has produced much of the 0.5° C rise, and the greenhouse effect is responsible for only a small part of that rise, that means that we can expect a temperature increase of less than 3° C in the next century.

Suppose, for example, that some combination of natural variability and solar variability were responsible for 0.3° C of the 0.5° C increase observed since 1880. This would mean the greenhouse contribution is only 0.2° C. If that is the case, the mid-to-late 21st century warming will be only around 1° C.

This is considerably less than the warming of 3° C indicated by current mid-range greenhouse forecasts, which assume that the entire post-1880 rise of 0.5° C is due to the greenhouse effect.

In fact, it is possible that a combination of natural and solar variability is the cause of the entire temperature increase observed since 1880, with the greenhouse effect relegated to a negligible

* "Since global climate models indicate the increase in greenhouse gases [in the past century] should have increased the temperature by 0.5° C, the modeling and observational evidence are consistent in indicating that the greenhouse effect is changing our climate." James Hansen, NASA Goddard Institute for Space Studies (*Washington Post*, February 11, 1989)

role.

The effect of the wild cards introduced into the greenhouse studies by natural and solar variability is that no conclusion about the magnitude of the greenhouse effect in the next century can be drawn from the 0.5° C warming that has occurred in the last 100 years.

V. EVIDENCE FOR NATURAL CYCLES OF WARMING AND COOLING

Is other evidence available that might be pertinent to a prediction of global temperatures in the 21st century? An analysis of climate records for England by Lamb indicates that during the last millenium, protracted periods of cold weather occurred roughly every 200 years — in the 13th, 15th, 17th, and 19th centuries. The best known of these cold periods was the Little Ice Age — a time of very low temperatures marked by failed harvests, famine and social upheaval in northern Europe. Temperatures in the Little Ice Age were roughly 1°C lower than they are today. The 1690s were perhaps the coldest decade on record in the history of Europe.

Wigley and Kelly have compiled additional evidence for the natural occurrence of cold periods every few centuries. Their climate history is drawn from global records compiled by Röthlisberger on the advance and retreat of glaciers.

The pattern of recurring cold periods reported by Wigley and Kelly on the basis of the glacial records is not as regular as Lamb's records. However, it has greater validity because the glacial data are global, while the Lamb climate record is regional and may be valid only for northern Europe.

Wigley and Kelly also discovered a correlation between the climate record and the record of solar activity going back over many centuries. The levels of solar activity were determined from measurements of the carbon-14 content of trees, compiled by Stuiver and Braziunas.* (See the appendix for an explanation of the

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* *Secular Solar And Geomagnetic Variations In The Last 10,000 years,* (Stephenson and Wolfendale, eds.), 245-266 (1988)

relation between carbon-14 and solar activity.) Comparing the carbon-14 record to their climate history, Wigley and Kelly found that six out of the seven most severe decreases in solar activity correspond closely to cold spells in the climate record. One of these is the famous period of about 50 years of very low solar activity in the 17th century, which coincided with the coldest period of the Little Ice Age.

Figure 8 shows the carbon-14 record during the last thousand years. The figure indicates surprisingly regular cycles of solar activity, with periods of low activity every 200 years or so during the last thousand years — midway between the 10th and 11th

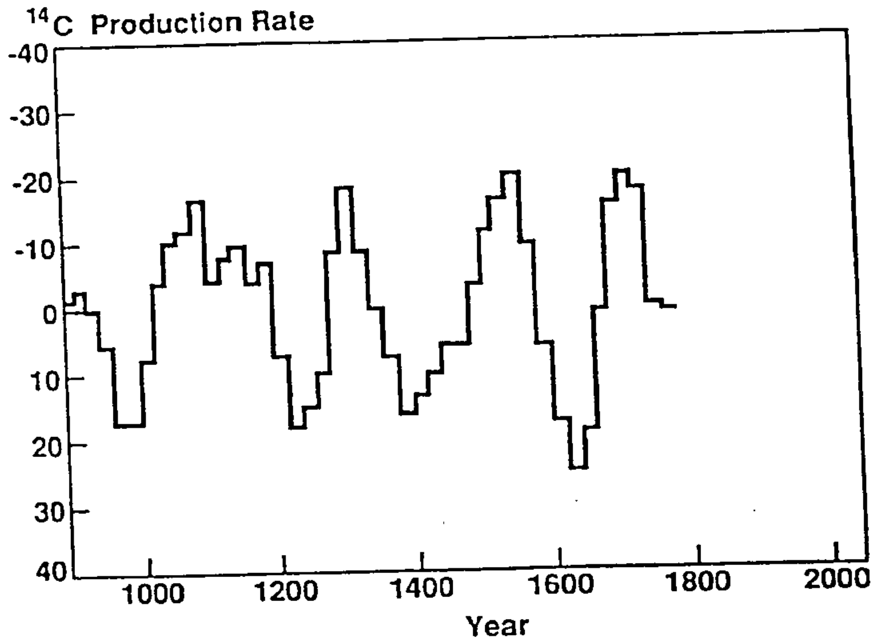

Figure 8. Anomalies in carbon-14 production rates associated with changes in solar activity. The negative of the production rate is plotted so that periods of low solar activity appear as low points on the chart. Dates are moved back 50 years to correct for the residence time of carbon-14 in the atmosphere.

centuries, and in the 13th, 15th, 17th and 19th centuries.

The carbon-14 record shows only the beginning of the period of low activity in the 19th century, because the interpretation of the carbon-14 production rates become less reliable after ca. 1800. However, sunspot records confirm that a minimum of solar activity also occurred in the 19th century, followed by a rise in the 20th century to the current high level of activity.

On the basis of this record, another period of low solar activity can be expected in the 21st century. If the correlation between low solar activity and low temperature continues, we can also anticipate a period of protracted cold in the 21st century as a result of the natural forces of climate change. If the 21st-century cooling is comparable to the Little Ice Age, the earth will be about 1° C colder as a result of natural factors alone than it has been in the 1980s.

VI. CONCLUSIONS

- Current forecasts of the man-made greenhouse effect do not appear to be sufficiently accurate to be used as a basis for sound national policy decisions.
- Forecasters cannot rely on the temperature increase observed in the last 100 years as an indicator of greenhouse warming in the next century.
- Procurement of top-line supercomputers for the major greenhouse forecasting groups could significantly diminish the level of uncertainty in the greenhouse forecasts, and would also lead to information on regional climate changes — in particular, the occurrence of regional droughts — which cannot be predicted with any useful degree of accuracy by the crude models currently in use.
- The total cost of supercomputing facilities for the major climate forecasting groups would be no more than $100 million. The investment would be cost-effective when viewed in the perspective of the large and potentially negative impact on the five-trillion-dollar U.S. economy, that could result from a premature decision based on inaccurate and possibly misleading forecasts.
- The reliability of the greenhouse forecasts also suffers from gaps in observations of clouds and oceans, and a poor understanding of processes vital to the determination of climate, such as moist convection. A stronger effort in global observations is as important as the provision of computing power.
- Observations and number-crunching power alone will not suffice to resolve the difficult public policy issues posed by the poor reliability of current forecasts. Added scientific man-

power is also needed. Fewer than 50 atmospheric scientists are working on greenhouse and climate forecasts in the entire U.S. The size of this group is entirely inadequate for the importance of the task these scientists are being asked to perform.

- Certainty will never be achieved in a matter as complex as the forecasting of climate for the coming century. However, it is our judgment that if a prudent investment is made in computing power, observing programs and added manpower, answers that have a usable degree of reliability can be provided for policy makers within 3 to 5 years. Through such an investment, the government can accelerate the pace of climate research to yield the necessary information in years rather than decades, so that timely action can be taken if needed.

APPENDIX

APPENDIX: CARBON-14 AND SOLAR ACTIVITY (Page 31)

Carbon-14 is made by cosmic rays striking the earth's atmosphere. During periods of peak sunspot activity, when the surface of the sun is very disturbed, solar particles and magnetic fields spread through the inner part of the solar system, deflecting cosmic rays and tending to keep them from the earth. As a result, during these times of vigorous solar activity the amount of carbon-14 made in the earth's atmosphere decreases.

During quiet periods in the sun, when sunspots decrease in number or disappear (e.g., the Maunder Minimum of the 17th century), the intensity of the sun's magnetic field decreases in the inner region of the solar system .

Some carbon-14 atoms made by cosmic rays reach the ground and are incorporated into the bodies of trees in the normal process of tree growth. Analysis of the carbon-14 content in a cross section of a tree trunk yields a picture of carbon-14 changes during the tree's lifetime. The resultant curve of carbon-14 abundance versus time is a measure of variations in sunspot numbers and solar activity over time.

The chart plots the negative of the variations in carbon-14, so that a minimum in the carbon-14 chart as plotted here also means a minimum in solar activity and sunspot numbers. Since carbon-14 atoms typically take many decades to reach the ground, for the purpose of comparison with times of occurrence of climate changes the carbon-14 record shown in the chart has been shifted back 50 years.

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GLOBAL WARMING

What Does the Science Tell Us?

EXECUTIVE SUMMARY

George C. Marshall Institute
Washington, D.C.

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Authors of

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What Does the Science Tell Us?

ROBERT JASTROW is Professor of Earth Sciences at Dartmouth College. Dr. Jastrow is founder and past director for 20 years of NASA's Goddard Institute for Space Studies, first Chairman of NASA's Lunar Exploration Committee and recipient of the NASA Medal for Exceptional Scientific Achievement.

WILLIAM A. NIERENBERG is a member of the Global Climate Subcommittee of the EPA, former Chairman of the Carbon Dioxide Assessment Committee of the National Academy of Sciences and member of the NAS Climate Research Board. Dr. Nierenberg served as the First Chairman of the National Advisory Committee for the Oceans and Atmosphere. He is Director Emeritus of the Scripps Institution of Oceanography of the University of California, San Diego.

FREDERICK SEITZ is Past President of the National Academy of Sciences and the American Physical Society and President Emeritus of Rockefeller University. Dr. Seitz is former Chairman of the Defense Science Board, former Science Advisor to NATO and recipient of the National Medal of Science.

December 1990

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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 feet[2] 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 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 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.

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 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 CO_2.

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 CO_2 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.

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.

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 satellites 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. Instead, 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.

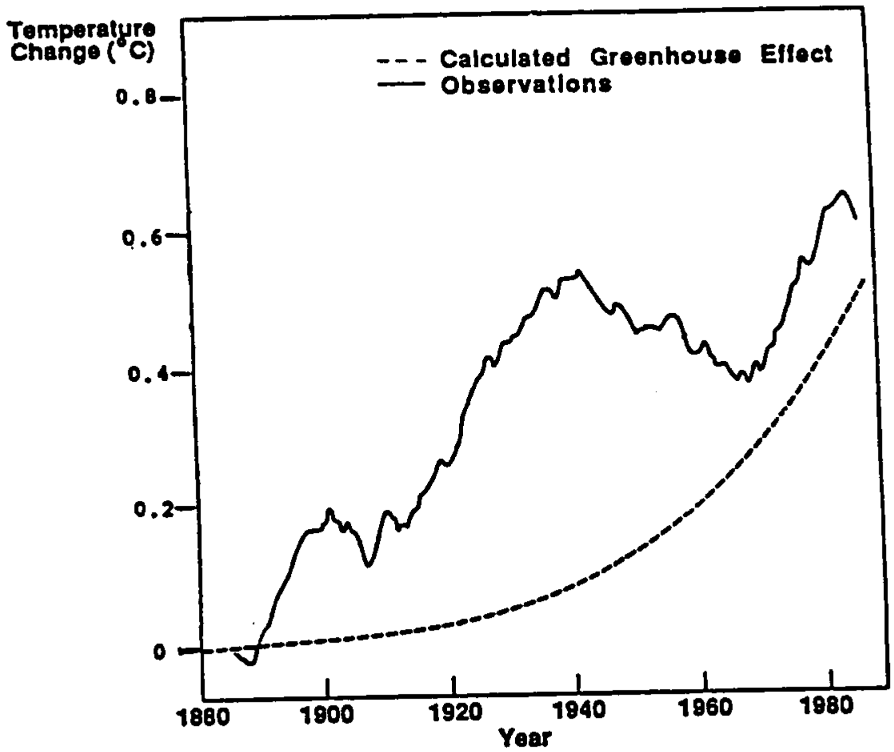

Figure 1. Comparison between observed global average temperature and calculations by Hansen *et al.*,[8] based on a computer simulation of the greenhouse effect. The dashed line indicates the calculated temperature increase caused by carbon dioxide increases since 1880. The solid line indicates the observed 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.

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]

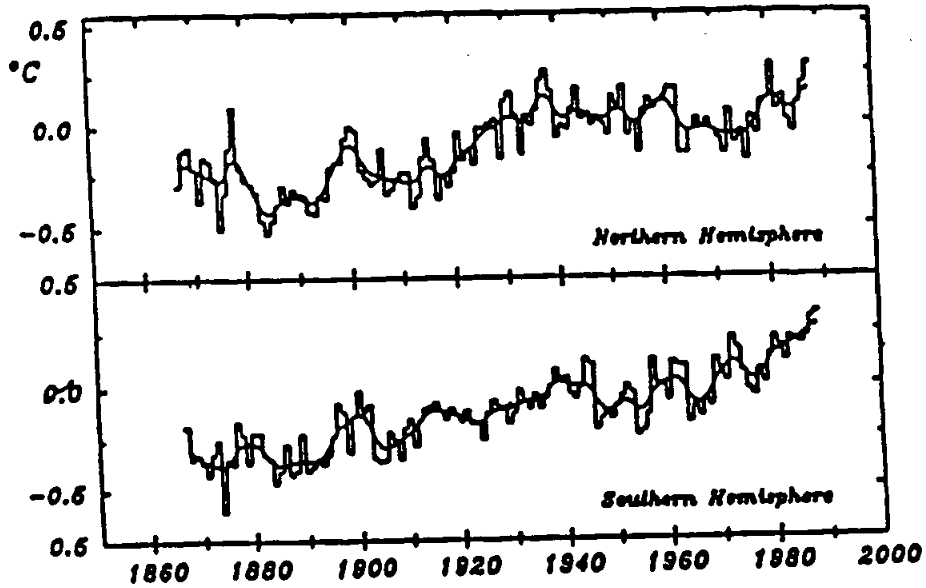

Figure 2. Northern and Southern Hemisphere temperature observations.

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).

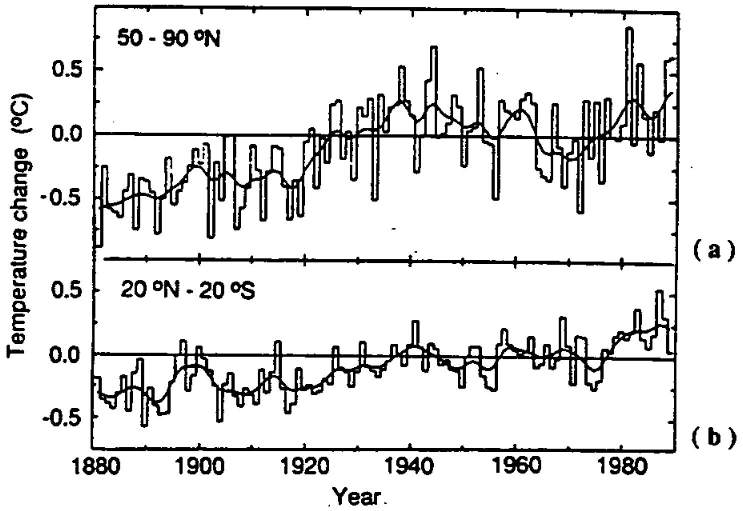

Figure 3. Observed variations in annual mean temperature in (a) high latitudes in the Northern Hemisphere and (b) the tropics.

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 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

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.

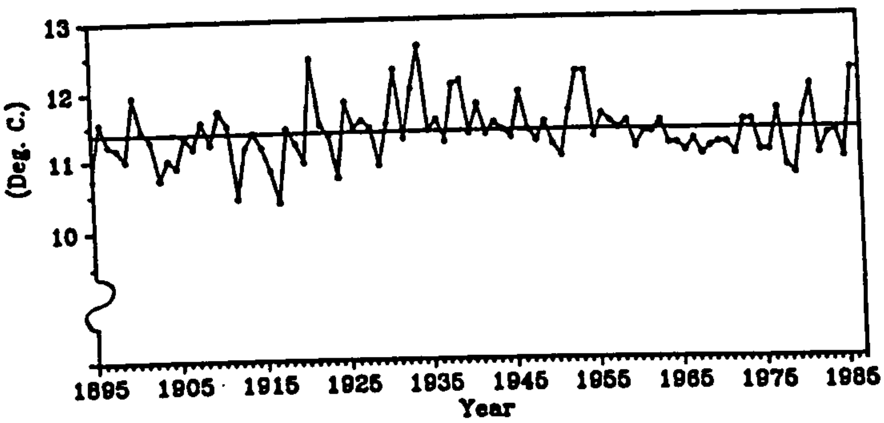

Figure 4. Annual average temperature for the contiguous United States 1900-1984, corrected for urban heat island effect.

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

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 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 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 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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GLOBAL WARMING UPDATE

RECENT SCIENTIFIC FINDINGS

George C. Marshall Institute
Washington, D.C.

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The George C. Marshall Institute
1730 M Street, N.W., Suite 502
Washington, D.C. 20036

Contents

I. INTRODUCTION

A great deal of research has been devoted in recent years to the technical problems involved in calculating the manmade greenhouse effect. This study, the third in a series by scientists associated with the George C. Marshall Institute, considers recent findings on the extent of human-induced global warming. One of the main reasons for concern over this aspect of climate change is the fact that the earth's temperature has risen by approximately half a degree Celsius in the last 100 years. This 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 in the atmosphere is apparently the result of human activity, such as burning coal, oil and gas.

Several scientific groups have concluded that the greenhouse effect caused by the manmade emissions of carbon dioxide and other gases has produced much or all of the recent rise in global temperatures. They predict that there will be an increase in greenhouse gases equivalent to a doubling of carbon dioxide by the middle of the 21st century, and that this will cause the temperature of the earth to rise by as much as 5°C.

According to these scientists, a temperature rise of this magnitude would cause major disruptions in the earth's ecosystem, including severe summer drought in the midwestern United States and other agricultural regions. The worst-case scenarios predict a major rise in sea level 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. The lives of hundreds of millions of individuals would be disrupted.

The available data on climate change, however, do not support these predictions, nor do they support the idea that human activity has caused, or will cause, a dangerous increase in global temperatures. As we make this statement, we are aware that it contradicts widespread popular opinion, as well as the technical judgments of some of our colleagues on the magnitude and importance of the greenhouse warming. But it would be imprudent to ignore the facts on global warming that have accumulated over the last two years. These facts indicate that theoretical estimates of the greenhouse problem have greatly exaggerated its seriousness.

Enormous economic stakes ride on forthcoming government decisions regarding carbon taxes and other restrictions on CO_2 emissions. Due attention must therefore be given to the scientific evidence, no matter how contrary to popular opinion its implications appear to be.

II. ARE THE GREENHOUSE FORECASTS RELIABLE?

Concentrations of carbon dioxide and other greenhouse gases in the atmosphere have increased substantially in the last 100 years, mostly as a result of burning coal, oil and gas, as well as other human activities. The increase in the totality of greenhouse gases is equivalent to a 50% rise in carbon dioxide. According to computer simulations of the greenhouse effect, this large increase in greenhouse gases should have produced a rise of about 0.5°C in the average temperature of the earth's surface. The dashed line in Figure 1 on the following page shows the 0.5°C temperature rise in the last 100 years, calculated from a theoretical model of the effect of greenhouse gases.

The theoretical result for the greenhouse effect is in good agreement with actual measurements of the average temperature on the earth's surface, shown as the solid line in Figure 1. The measurements reveal that the earth's temperature has gone up about 0.5°C since 1880. This agreement seems to suggest that the increase in greenhouse gases was the cause of the temperature rise. It implies further that the greenhouse predictions for the next century must be taken seriously.

However, another look at Figure 1 places this conclusion in doubt. The chart shows that nearly the entire observed rise of 0.5°C occurred before 1940. However, most of the manmade carbon dioxide entered the atmosphere after 1940. The greenhouse gases cannot explain a temperature rise that occurred before these gases existed.

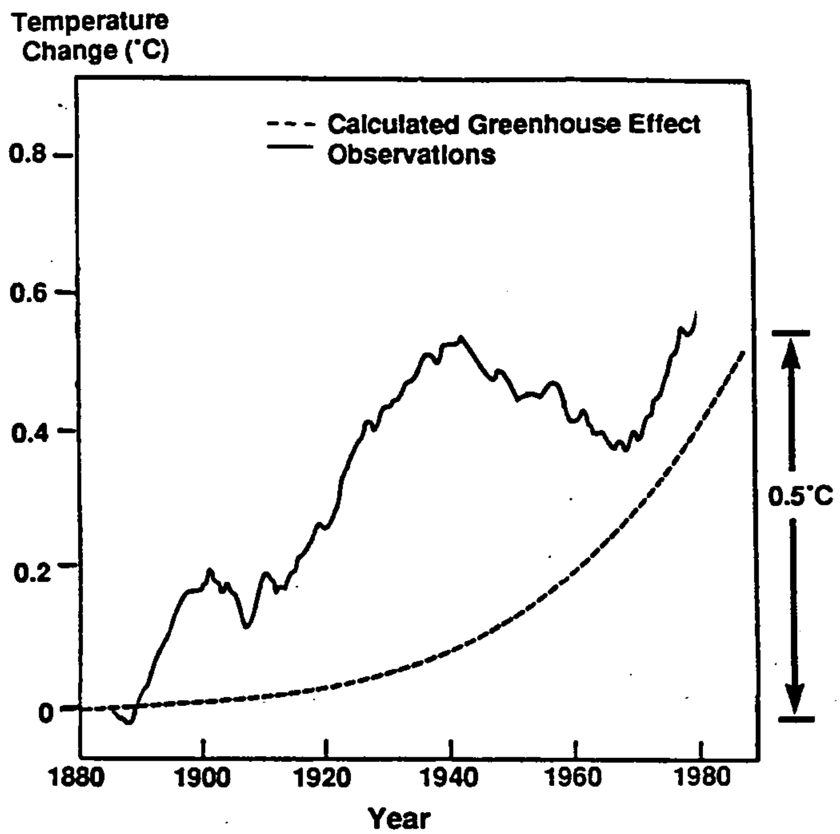

Figure 1. Calculated warming due to the increase in greenhouse gases in the last 100 years (dashed line), compared with observed temperature changes (solid line). [1]

Furthermore, from 1940 to 1970, carbon dioxide built up rapidly in the atmosphere. According to the greenhouse calculation, the temperature of the earth should have risen rapidly. Instead, the chart shows that the temperature actually *dropped.*

The fall in temperature between 1940 and 1970 is particularly difficult to explain as a greenhouse phenomenon, because, as noted, this entire period was one of strong economic growth and increasing emission of greenhouse gases. According to the greenhouse predictions, it should have been a period of rapidly accelerating temperature rise. Even allowing for a delay in the earth's response to the increase in greenhouse gases, the 1970s should have been appreciably warmer than the 1940s.

The fact that this was not the case indicates that the greenhouse effect could not have been the only cause or even the principal cause of the climate change that took place between 1880 and 1970. As the report of the U.N. Intergovernmental Panel on Climate Change states:

> "It is still not possible to attribute any or all of the warming of the last century to greenhouse gas-induced climate change."[2]

Heating by greenhouse gases cannot explain the rapid rise in temperature prior to 1940, and cannot explain the fact that the temperature dropped between 1940 and 1970. *The predictions of the greenhouse theory are contradicted by the temperature record to such a degree as to indicate that the anthropogenic greenhouse effect has not had any significant impact on global climate in the last 100 years.*

The Missing Greenhouse Signal

There are other checks on the reliability of the greenhouse forecasts. These forecasts are based on computer simulations of global climate that not only predict a general warming of the earth, but also predict certain special characteristics of the warming. These special characteristics make up the so-called *greenhouse signal.*

For example, calculations of the greenhouse effect show a particularly large temperature increase at high latitudes. A pattern of warming that showed greater temperature increases at high latitudes than at low latitudes would be a sign that the greenhouse effect is probably the cause of the warming. It would be a "greenhouse signal."

According to the climate calculations, several types of greenhouse signal should have appeared clearly in the temperature records for the last 100 years. The detection of these signals would indicate that the greenhouse effect is already substantial and the greenhouse theories are relatively reliable.

Warming in the Northern Hemisphere. All the greenhouse calculations predict that there should have been more warming in the Northern Hemisphere than in the Southern Hemisphere, as a result of the increase in greenhouse gases in the last 100 years. According to these calculations, the Northern Hemisphere should already be warmer than the Southern Hemisphere by about 0.5°C.[3] *However, the observed temperatures show no significant difference in temperature trends in the two hemispheres.*[4] (Figure 2, p. 7)

Warming at High Latitudes. The greenhouse computations also predict more warming at high latitudes than at tropical latitudes, particularly in the Northern Hemisphere. According to one representative calculation, the high latitudes should already have warmed by about 1°C more than the low latitudes as a consequence of the greenhouse warming.[5] *However, the temperature records shown in Figure 3 (p. 8) indicate no significant difference in trends between the high and low latitudes.*

In fact, the records for the period after 1940 show no net warming trend at all, although it was in this more recent period that most of the greenhouse gases entered the atmosphere. Instead, the charts show a greater warming trend at low latitudes than at high latitudes in the last 50 years —

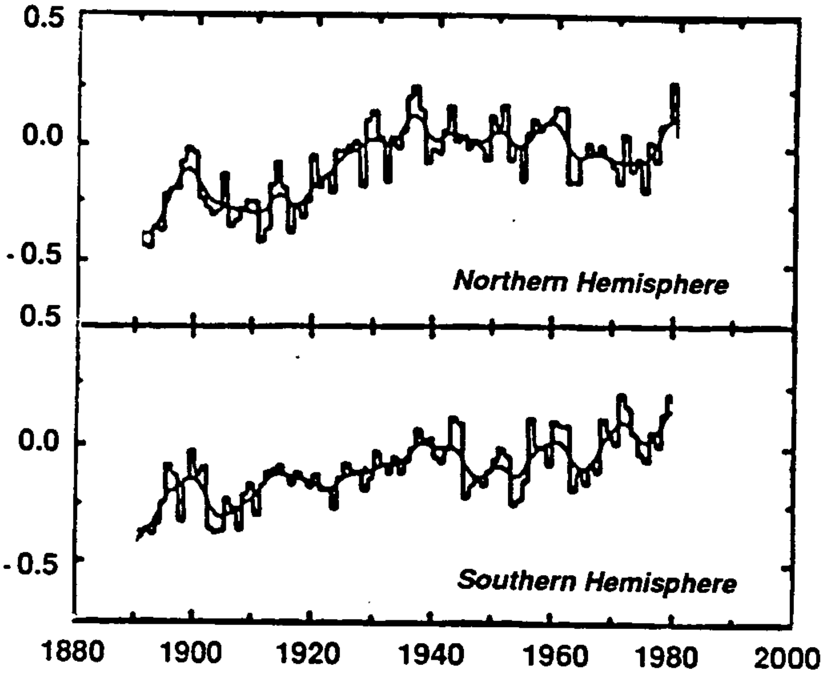

Figure 2. Observations of mean temperature in the Northern and Southern Hemispheres.

directly opposite to the greenhouse predictions.

Warming in the U.S. According to other greenhouse computations, the continental U.S. should have warmed 0.5-1.0°C in the last 100 years, with most of the warming expected in the last 50 years. *However, a compilation of temperature records for the U.S. reveals no statistically significant warming trend over the last 50 years.*[6] (Figure 4, p. 9) It is striking that in the largest area in the world for which reliable, well-distributed temperature records are available, the greenhouse predictions are not confirmed.

Rapid Warming in the 1980s. Moreover, the greenhouse theory indicates that a rapid rise in global temperatures should have occurred in the 1980s, as a result of the large

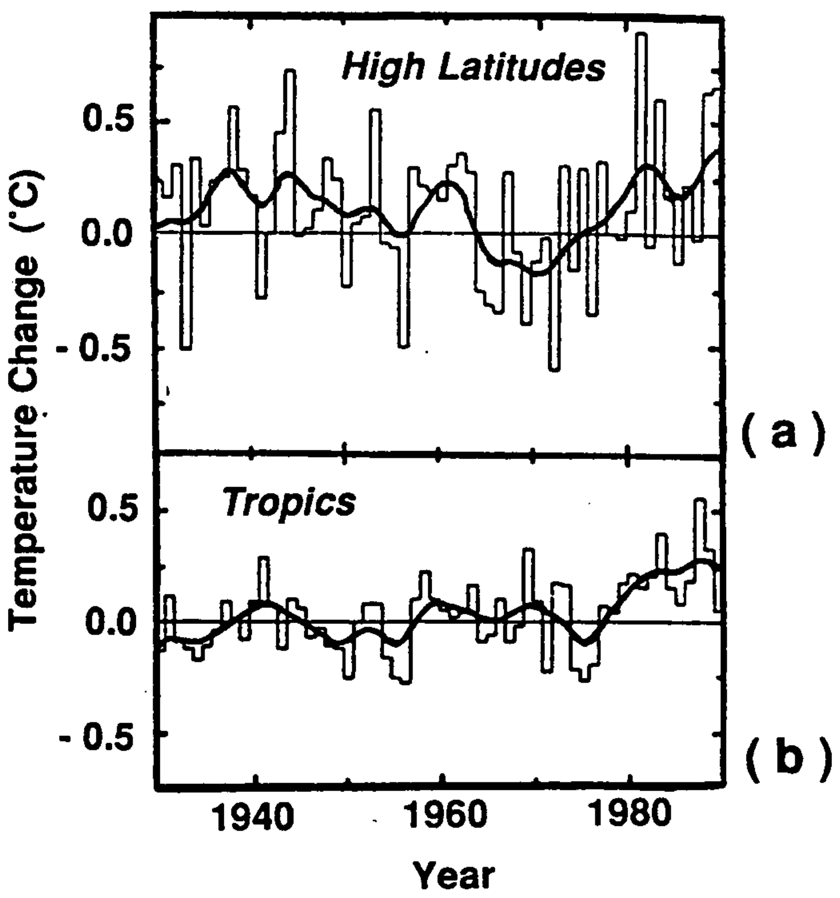

Figure 3. Observed variations in annual mean temperature in (a) high latitudes in the Northern Hemisphere; (b) the tropics.

increase in greenhouse gases in recent years. *However, precise satellite measurements of global temperatures show no significant warming during the 1980s.*[7] Figure 5 (p. 9) shows the results of satellite measurements of the earth's temperature, obtained by looking down at the surface of the planet from above.

The satellite results do not show the predicted trend to

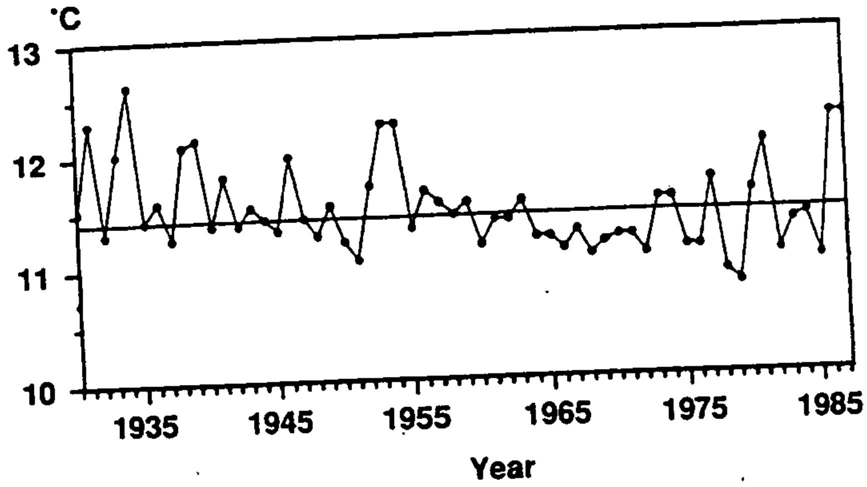

Figure 4. Annual average temperature for the contiguous U.S. 1900-1984, corrected for urban heat island effect.

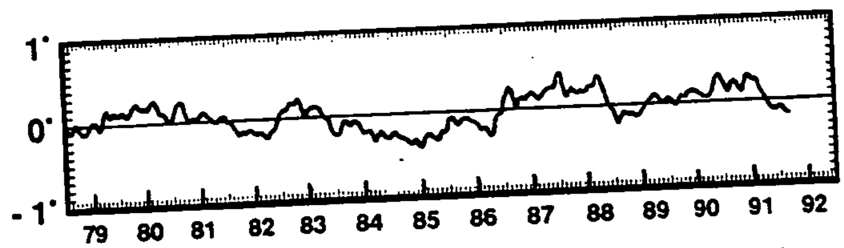

Figure 5. Satellite measurements of global average temperatures from 1979-1991. The data show an average increase of 0.06°C over the decade of the 1980s. The 1992 IPCC Report gives 0.3°C/decade as the consensus of the computer models for the increase in greenhouse warming over a decade — five times the observed increase in the 1980s.

higher temperatures in the 1980s. Temperature increases in some years are balanced by decreases in others. The average increase in the satellite data is 0.06°C/decade. The IPCC report gives .3°C/decade as the consensus of the theoretical predictions for the greenhouse-induced temperature increase.[8] *The greenhouse calculations appear to have exaggerated the magnitude of the greenhouse warming by roughly a factor of five.*

The accuracy of the satellite measurements can be tested by comparing them to temperatures obtained from ground stations in the U.S. Surface temperature measurements in the U.S. are well distributed and accurate, and do not suffer the defects of spotty coverage associated with the global network of surface stations. The correlation coefficient between satellite and surface measurements for the U.S is 0.98 — essentially a perfect correlation and a confirmation that the satellite data accurately represent the temperatures on the earth's surface.

In sum, the greenhouse calculations predict that during the last 50 years we should have detected: (i) a greater temperature rise in the Northern Hemisphere than the Southern Hemisphere; (ii) a greater temperature rise at high latitudes than at low latitudes; (iii) a substantial warming in the U.S.; and (iv) an accelerating global warming in the 1980s, reflecting the rapid increase in greenhouse gases in recent years.

None of these predictions is supported by the changes in climate that have actually been observed in the last 50 years. The greenhouse signal, which should have been readily detectable in temperature records, is not present.

It is clear that since the greenhouse gases have a heat-insulating effect, some degree of warming is likely to occur if their concentration in the atmosphere is increased. The question is: How much? If the greenhouse effect were as large as the commonly accepted forecasts predict, it would have produced a clear greenhouse signal in the temperature records of the last 100 years. But the signal is not present. Apparently, the greenhouse effect is considerably smaller than has been estimated.

Explanations Offered for the Failure of the Greenhouse Predictions

Atmospheric Pollution. Atmospheric pollution has been suggested as an explanation for the fact that the planet has not warmed as much as predicted by the greenhouse theories.[9] A large part of the pollution consists of sulphur dioxide emitted by burning fossil fuels in heavily populated and industrialized regions. Sulphur compounds in the atmosphere form a haze or smog of very small particles — called aerosols — that shield the surface from the sun's rays and cool the earth. The aerosols also form nuclei for the condensation of cloud particles, increasing the amount of cloud cover and cloud brightness. The increased cloud cover further shields and cools the earth.

Effect of Pollution on Northern Hemisphere Temperatures. The cooling effect of the pollutant particles or aerosols should be particularly great in the heavily industrialized Northern Hemisphere. Consistent with this expectation, satellite data indicate a higher concentration of aerosols in the Northern Hemisphere than in the Southern Hemisphere.[10] Charlson and others have suggested that this cooling effect of pollution-generated haze and clouds may cancel much of the warming effect of the greenhouse gases in the Northern Hemisphere.[11,12]

However, an excess of Northern over Southern Hemisphere aerosols would not, in itself, explain the failure of the Northern Hemisphere to warm as predicted. For that explanation to be valid, the concentration of Northern Hemisphere aerosols would have to have been increasing rapidly at the same time that the greenhouse gases were increasing. If the concentration of Northern Hemisphere aerosols were approximately constant in time, this unchanging factor could not mask the effect of a rapid rise in the concentration of greenhouse gases in recent decades. Northern Hemisphere temperatures would be lowered uniformly by the aerosols, but a rising trend due to the accelerating greenhouse effect would still be apparent against the constant background.

But Thomas Karl of the National Climate Data Center points out that sulphur emissions in the U.S. have neither been increasing rapidly, nor have they been approximately constant. They have, in fact, been decreasing in the U.S. since 1970.[13] Therefore, they could not have masked the expected greenhouse temperature increase in the U.S.

Is it possible that pollution in Eastern Europe and the former USSR has spread to the U.S. and masked the greenhouse effect here? Aerosol pollution in these regions, which has probably increased in recent decades, could be carried to the U.S. by the large-scale circulation of the atmosphere, thus explaining the fact that the U.S. has not warmed in recent years.

However, this explanation cannot be valid, because the lifetime of anthropogenic aerosols in the atmosphere is only a matter of days.[14] Thus, pollution originating in Eastern Europe, and travelling eastward with the general circulation of the atmosphere, does not stay in the air long enough to affect conditions in the U.S.*

Karl, et al. also note that no evidence exists for the view that an increase in cloud cover has been caused by pollution. The regions and seasons of increased cloud cover within the U.S. do not correspond with the regions and seasons of maximum pollutant concentration, as would be expected if pollution were the cause of the increased cloud cover. [15]

Delays in Warming Caused by Oceans. The warming of

* The general movement of air masses in the Northern Hemisphere is from west to east. Pollution originating in Europe must travel nearly 3/4 of the way around the globe to reach the U.S. The trip takes weeks, but, as noted, the aerosols are washed out of the atmosphere in days.

the earth lags behind the actual increase in greenhouse gases because the oceans absorb much of this heat, but warm up very slowly. It has been suggested that this delay in warming caused by the oceans can amount to decades or even centuries, and may account for the fact that the greenhouse signal has not yet appeared in the temperature record.[16]

However, the calculations including the effect of ocean circulation demonstrate a much shorter delay, with approximately 3/4 of the full warming appearing in the first 10 years after the increase in greenhouse gases takes place.[17] (Figure 6) The effect of this delay on the greenhouse warming to date would be a reduction of 0.1 °C, which is not enough to explain the absence of the greenhouse signal.

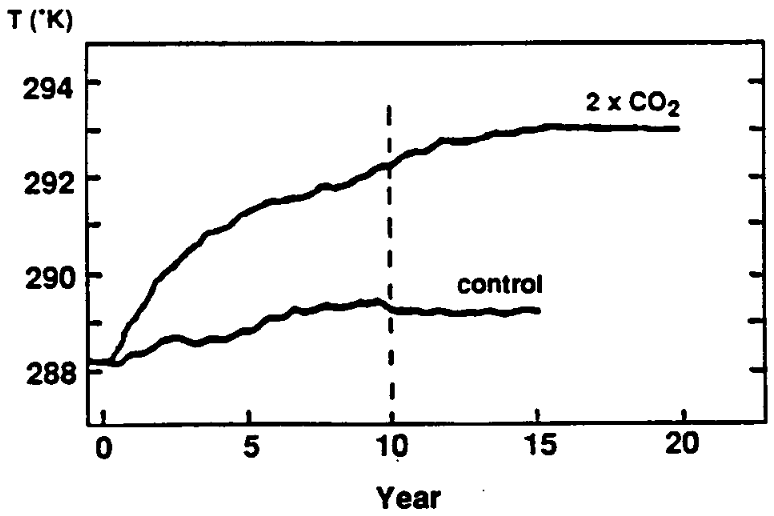

Figure 6. Globally averaged surface-air temperature versus time, showing the response of the earth's climate to a doubling of CO_2. The calculations, which include the effects of ocean circulation, show that approximately 3/4 of the full warming produced by CO_2 occurs within 10 years.

Reasons for the Poor Quality of the Greenhouse Forecasts

It is straightforward to calculate the temperature increase directly caused by the addition of greenhouse gases to the atmosphere. These gases absorb certain wavelengths in the infrared radiation emitted from the planet's surface. The amount absorbed can be calculated from properties of the greenhouse gases that have been measured in the laboratory. The absorbed radiation heats the atmosphere. The atmosphere radiates part of the absorbed heat up to space and part back to the surface of the earth. The heat returned to the earth's surface increases its temperature, producing the greenhouse warming. These processes constitute the direct heating effect of the greenhouse gases.

For a greenhouse gas increase equivalent to a doubling of carbon dioxide, which is projected to occur in the next 50 years or so according to the 1990 IPCC report, the calculation indicates that the temperature increase caused directly by the greenhouse effect is approximately 1°C.

In that case, why do the greenhouse theories predict temperature increases of as much as 5°C?

The answer is that the modest warming, which is the direct effect of the greenhouse gases, is amplified by "feedbacks" in the climate system. One of the most important feedbacks involves clouds. The greenhouse heating may lead to the formation of more clouds, shielding the earth's surface and cooling the planet. That would make the net warming less than 1°C. The increase in cloud cover would be a *negative feedback.*

Or the greenhouse warming may lower the relative humidity of the air, leading to the formation of fewer clouds. That means more sunlight reaches the ground, and the final warming is greater than 1°C. In this case, the clouds

ERRATUM

Endnote "24" should read: Miller, G. and A. deVernal, *Nature* 355, 245 (1992).

have created a *positive feedback*.

Which is correct? Do clouds make the greenhouse effect larger or smaller? No one knows. In a recent study of the greenhouse effect, the U.K. Meteorological Office made a change in the properties of the clouds assumed in the calculation and found that the predicted greenhouse warming dropped from 5.2°C to 1.9°C. Results obtained by other climate forecasting groups range from a warming of less than 1°C in the next century to as much as 5°C, largely as a consequence of the different assumptions by each group regarding cloud feedbacks and other types of feedbacks.

A global warming of 1°C, spread over 50 years or more, might not matter much, but 5°C would be a serious problem. Narrowing this enormous range of uncertainty would require calculating, *inter alia*, how large the cloud feedback is, and whether it is positive or negative, and that presents an extremely difficult problem for the climate forecaster.

III. THE CAUSE OF RECENT CLIMATE CHANGES

Yet the earth's temperature did rise in the last 100 years. Since there is no discernible greenhouse signal in the temperature record, and moreover, most of the temperature rise occurred before the bulk of the greenhouse gases were in the atmosphere, it is clear that the rise was not caused by the greenhouse effect. But what *did* cause the earth to become warmer in that interval?

In 1991, a paper appeared in *Science* which shed light on this question.[18] This paper was based on a new analysis of changes in the sun. It showed an almost perfect correlation between the ups and downs of solar activity on the surface of the sun and the ups and downs of global temperature change.

The correlation is shown in Figure 7 on the following page. The figure shows that all the significant changes in global temperature in the last 100 years faithfully track the changes in solar surface activity. The agreement is too close to be readily dismissed as coincidence. This close correlation is in contrast to the marked disagreement between the global temperature record for the last 100 years and the predictions of the greenhouse theory, shown in Figure 1.

What physical mechanism can explain the correlation

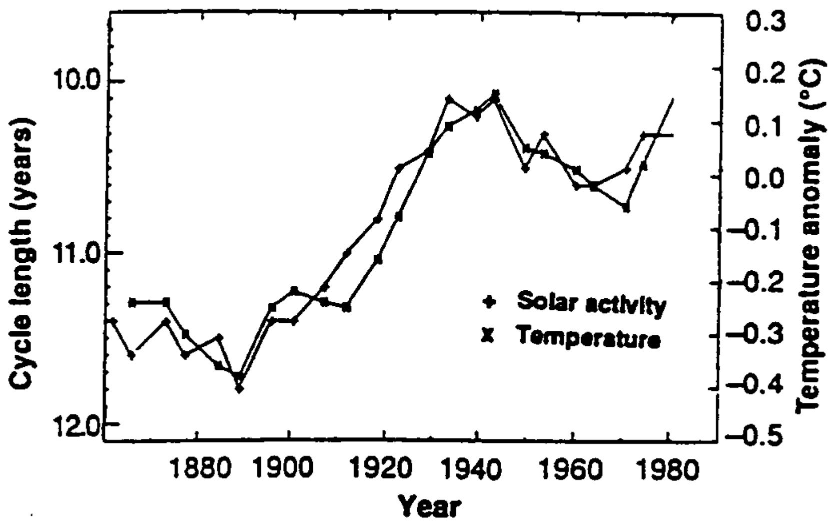

Figure 7. Comparison between global temperatures (x) and solar surface magnetic activity, measured by the length of the solar cycle(+). The cycle length has an inverse correlation with sunspot numbers: short cycles mean high sunspot numbers and a high level of surface magnetic activity.

between global climate and the sun's surface magnetic activity? This magnetic activity is caused by strong magnetic fields which erupt on the sun's surface in sunspots, bursts of energetic particles and radiation. The changes in the surface magnetic fields do not in themselves transfer enough energy to the earth and its atmosphere to have a direct impact on climate.

However, satellite observations of the sun have shown that when its surface magnetism changes, its energy output also changes. When the sun's surface magnetic activity goes up, its energy output increases; when the surface magnetic activity diminishes, its energy output decreases.

Apparently, the changes in surface magnetism and changes in energy output are two independent manifestations of a deeper phenomenon occurring in the body of the sun — two effects of one underlying cause.*

The satellite measurements are available thus far for only the 10-year period 1978-1988, for which they show a change of 0.1% in solar energy output. This variation is too small to explain the global temperature changes observed in the last 100 years. However, larger variations in the sun's magnetism occur over timescales of centuries, and may be accompanied by correspondingly larger changes in the sun's energy output. Studies of convection in the sun indicate that changes in the state of the magnetic field within the sun's convective zone could, in fact, produce changes in solar luminosity of the order of 1%. An increase of 0.5-1.0% is estimated to be sufficient to explain the entire 0.5°C global warming of the last 100 years.

Baliunas, et al. have combined observations of the sun and solar-type stars to obtain the relationship between solar luminosity and changes in the sun's surface magnetic activity.[19] Their results indicate that the marked increase in

* One possible physical mechanism relating solar magnetism to solar luminosity is the inhibiting effect of magnetic fields in the solar interior on convective energy transport in the sun.

Suppose, for instance, that when the surface of the sun is not erupting in sunspots and flares, the magnetic field in the solar interior is a smooth, well-ordered azimuthal field. At such times, this subsurface field is most effective in blocking the convective transport of energy to the surface, and the sun's luminosity decreases. At these times, the surface is also relatively quiet and undisturbed, i.e., the sun is at a minimum in its 11-year cycle.

When the surface of the sun is magnetically active, with many sunspots, it is plausible to assume that the subsurface magnetic field is in a relatively disordered state. At such times, the field is less effective in blocking the transport of energy, hence the sun is more luminous.

These qualitative conclusions agree with the satellite observations, which show that the sun's luminosity and surface magnetic activity rise and fall in phase. The key to the physical mechanism is the suggestion that when the average magnetic field on the sun's surface is at a minimum, the subsurface field is at a maximum.

solar surface activity recorded in the last 100 years corresponds to a brightening of the sun by 0.7%, in good agreement with the estimated change in solar brightness needed to explain the recent global warming.

Additional Evidence for Solar Control of Climate. Figure 7 suggests that the sun, and not the greenhouse effect, has been the controlling factor in climate changes over the last 100 years. However, this is not the only evidence for a connection between the sun and climate change. Other evidence for a sun-climate connection extends over thousands of years of geological records.

Records of changes in the amount of C-14 in tree rings — an isotope of carbon which is known to be a good indicator of levels of solar magnetic activity — reveal that during the last 6,000 years, solar activity has risen and fallen by substantial amounts every 200-300 years. Figure 8 (p. 20) shows one of the carbon-14 records. A comparison between the carbon-14 record and the record of ancient climates, obtained from geologic evidence of the advance and retreat of glaciers, reveals that all but one of the major decreases in solar activity in the last 8000 years were accompanied by cold spells in the climate record.

The most recent and best-known instance was the Little Ice Age of the 17th century. This cool period in the earth's climate history coincided with the pronounced 17th-century lull in solar activity known as the Maunder Minimum.

Evidence for a Small Greenhouse Effect

Figure 7 shows changes in solar activity and changes in global temperatures in the last 100 years so closely correlated that the two curves seem to be wrapped around one another. This close correlation suggests a means of estimating

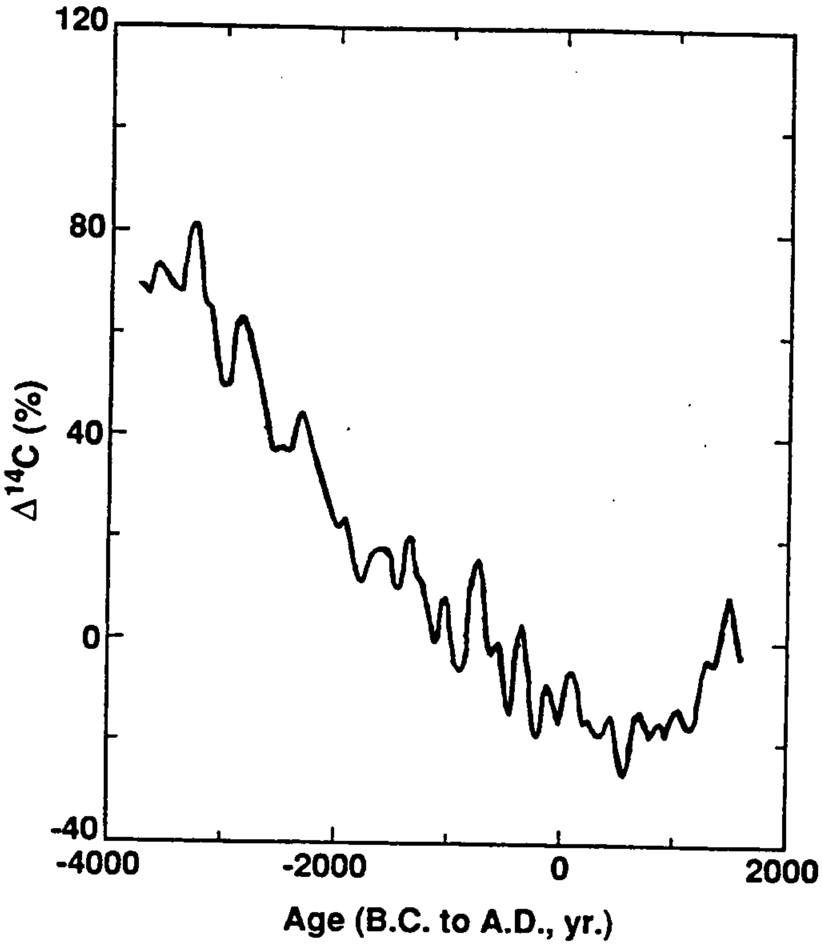

Figure 8. Concentrations of Carbon-14 in tree rings over the last 6,000 years, resulting from changes in solar magnetic activity. The average peak-to-peak separation is approximately 200 years. The decline from 4,000 B.C. to 500 A.D., and subsequent rise, are the product of long-term changes in the geomagnetic field and are not related to solar activity.

a limit to the size of the greenhouse effect.

As noted on page 4, the calculations of the greenhouse effect show that prior to 1940 its climate impact must have been fairly modest, no more than 0.1°C. Thus, the greenhouse effect could not have been responsible for the entire 0.5°C rise that was observed to occur prior to 1940. An increase in the sun's brightness is a more likely candidate for the cause of that early rise.

However, according to the calculations, after 1940 the greenhouse effect should have increased rapidly. Thus, if the calculations were correct, in the post-1940 period the pattern of global temperature changes should have begun to show a marked divergence from the pattern of solar activity changes, as greenhouse gases began to have an appreciable impact on the climate. The divergence should have become particularly pronounced in recent decades.

But this gradually developing separation between the temperature chart and the solar activity chart does not appear. The agreement between the two charts continues to be remarkably close after 1940. Allowing for the uncertainties in both charts, room remains for only a very small greenhouse contribution of a few tenths of a degree at most, in the post-1940 period.

As noted, the increase in the concentration of all the greenhouse gases in the last 100 years is equivalent to a 50% rise in the amount of carbon dioxide in the atmosphere. It appears that this increase has produced a modest global warming of no more than a few tenths of a degree. If the 50% increase in carbon dioxide up to the present time has produced a warming of a few tenths of a degree, the 100% rise projected for the next century will produce a warming of twice that amount, or roughly half a degree in round numbers.

This upper limit on global warming in the next century is five times smaller than the value cited in the IPCC report as "the best estimate" for the magnitude of the greenhouse effect produced by a 100% rise in CO_2. It is, however, consistent with the greenhouse warming inferred from satellite temperature measurements (p. 9).

IV. NEW RESULTS ON GLOBAL FLOODING

Major new findings relating both to the greenhouse effect and to its impact on human affairs appear almost monthly in the technical literature. With roughly one billion dollars a year going into climate change research in the U.S. alone, such rapid progress is not surprising. New results on the magnitude of the threat posed by global warming have already been reported in the first two months of 1992.

Threat of Major Floods

Melting of the polar ice sheets and a consequent rise in sea level have been viewed as among the most alarming potential effects of the greenhouse warming. An increase in sea level of several feet, projected by some experts, would cause destructive flooding of low-lying areas over the entire globe. The 1990 IPCC report gives a "best estimate" of about 66 cm. (2 feet) for the sea level rise expected from the greenhouse effect in the next century.[20] A March 1992 press article refers to global warming as the source of "rising seas inundating island nations, wiping out coastal marshlands and creating millions of environmental refugees."

New Evidence for a Future Drop in Sea Level. However, recent research indicates that sea levels will fall rather than rise in response to the greenhouse warming. In 1992, a Canadian-American team of scientists reported that the warming could be expected to lead to a growth in the size of the ice sheets, locking up more water and causing sea levels to drop by as much as two feet in the next century.[21]

Their conclusions were based on an examination of the geological record over the last 130,000 years. This examination indicated that a warm climate, similar to that projected by greenhouse calculations for the next century, favored the formation and growth of ice sheets, rather than their shrinkage.

How can a temperature increase cause ice sheets to grow? The answer to this seeming paradox is that Arctic and Antarctic air is normally too cold to hold much moisture. Therefore, these regions experience relatively little snowfall. With rising temperatures, the air holds more moisture, snowfall increases, and the size of the ice sheets also increases.

In 1980, some experts considered a 25-foot rise in sea level in the next century to be a possibility.[22] In 1985, the estimate was reduced to three feet.[23] In 1989, it was reduced again to one foot. Now the predicted "rise" has passed through zero heading downward, and become negative.[24] (Figure 9, p. 24) According to these results, the problem of rising sea levels and destructive floods has disappeared for the foreseeable future.

Lessons Drawn from the History of Sea Level Predictions. Two lessons may be learned from this series of developments. One is that the flooding of coastal cities and low-lying islands like the Maldives no longer appears to be a serious possibility. That is important, because some journalists and policymakers still refer to a catastrophic rise in sea level as a major threat requiring prompt measures aimed at restricting the burning of coal, oil and gas.

The second lesson is that the apocalyptic forecasts of scientists in this area must be greeted with extreme caution, if not skepticism, by policymakers and the public. If the government had undertaken a massive program for construction of seawalls on the U.S. coast five or ten years ago on the basis of what was then the accepted scientific wisdom, policymakers would look foolish now and a great deal of money would have gone into a wasteful and fruitless effort.

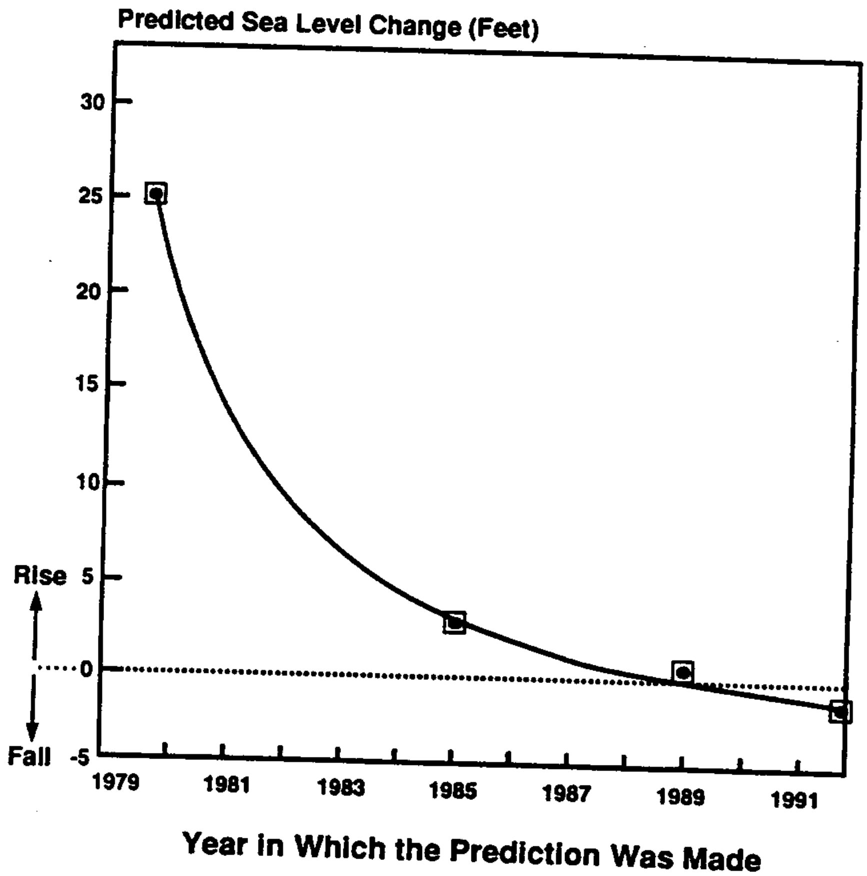

Figure 9. Predicted change in sea level resulting from the greenhouse effect, plotted against the year the prediction was made.

V. CONCLUSIONS

Computer simulations of the earth's climate predict how much warming will result from a doubling of today's levels of carbon dioxide in the atmosphere — a condition that could be reached in the second half of the 21st century. The results obtained from the computer models used by various scientific groups range from roughly 1°C to 5°C, with 2.5°C as the "best guess" proposed by the U.N. Intergovernmental Panel on Climate Change.

Reduced Estimates of the Greenhouse Effect. If the greenhouse effect were as large as any of the results yielded by these computer models, the effect would already have shown up clearly in the temperature record. The fact that the expected "greenhouse signal" is missing from the record suggests that the computer models have considerably exaggerated the size of the greenhouse effect.

Additional evidence, reported in the last year and based on satellite measurements of global temperatures, indicates that the greenhouse warming produced by a doubling of CO_2 in the next century will be less than 1°C, and may be as small as 0.5°C.

Independent support for this conclusion comes from a comparison between changes in solar activity and changes in global temperature. The very close correlation between the solar changes and the changes in temperature suggests that the sun has been the controlling influence on climate in the last 100 years, with the greenhouse effect playing a smaller role. The solar data and the temperature data fit so closely in their time dependence as to imply that the greenhouse contribution to global warming up to the present time cannot be more than a few tenths of a degree. If the concentration of greenhouse gases rises in the course of several decades by an amount equivalent to a 100% increase in carbon dioxide, as some have predicted, the warming to be expected in the next century may be as large as twice a few tenths of a degree, or 0.5°C in round numbers.

Spread over a number of decades, a warming of half a degree would be a relatively small effect and lost in the noise of natural climate fluctuations.

These limits, while approximate, have more validity than the theoretical estimates of climate change, because they are not based on computer programs simulating the earth's climate but on the response of the real climate to a real increase in greenhouse gases over the last 100 years.

VI. POLICY IMPLICATIONS

Recent findings, based on observations of actual temperature changes, suggest that the greenhouse warming will be considerably smaller than commonly accepted estimates based on computer simulations. Temperature increases in the next century, assuming a greenhouse gas increase equivalent to a doubling of carbon dioxide in the atmosphere, will almost certainly be less than 1°C and may be less than 0.5°C. Temperature changes of this magnitude are commonplace in the earth's recent history, and are not a particular cause for concern.

How do the new results affect energy policy? Some scientists and policymakers want the U.S. to adopt laws severely restricting carbon dioxide emissions, because they regard carbon dioxide as the primary cause of global warming. Congress has asked the Department of Energy for an estimate of the cost of policies that would reduce carbon dioxide emissions by 20% in the next 10 years. According to the Department of Energy, the cost at the end of the decade can be as much as $95 billion/year. The cost of electricity would double. The cost of oil would increase by $60/barrel, and gasoline would go up $1.30/gallon. A privately funded study estimates an accumulated cost of $3.6 trillion over the next 100 years for comparable restrictions.[25,26]

But the scientific evidence does not support a policy of carbon dioxide restrictions with its severely negative impact on the U.S. economy. Important new findings on the greenhouse effect and global warming are reported nearly every month. Several of the major findings discussed in this report were released in the last year. Suppose policymakers wait five years to get still more results, before undertaking the drastic measures proposed by concerned scientists and politicians. What will that cost the U.S.?

The Marshall panel did a study on this problem, using data from the 1990 report of the U.N. Intergovernmental Panel on Climate Change. M.E. Schlesinger and X. Jiang did a similar study.[27] Both studies yielded the same answer. A five-year delay on major policy decisions regarding carbon dioxide limits will lead to a small amount of additional warming in the next century. How small will the additional warming be?

The calculations show that a five-year delay in limiting carbon emissions will make the world warmer in the next century by at most one tenth of a degree, compared to how warm it would be if there were no delay.

A very rapid evolutionary process is occuring in the field of greenhouse research, with major improvements likely in basic understanding and in the accuracy of the greenhouse forecasts in the next few years. An additional warming of one tenth of a degree in the 21st century is a very small penalty to pay for better information on government decisions that, if taken unwisely, can be extraordinarily costly to the U.S. economy.

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LINDZEN

BEFORE THE MINNESOTA PUBLIC UTILITIES COMMISSION

In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minn. 1993, Chapter 356, Section 3	))))	Docket No. E-999/CI-93-583

REBUTTAL TESTIMONY OF DR. RICHARD S. LINDZEN

Sponsored By:

Western Fuels Association, Inc.
Lignite Energy Council
Center for Energy and Economic Development
State of North Dakota

March 15, 1995

REBUTTAL TESTIMONY OF DR. RICHARD S. LINDZEN

Q.1. State your name, position, and qualifications in the area of climate modelling and dynamics.

A. My name is Richard S. Lindzen. I hold the Alfred P. Sloan Professorship of Meteorology at the Massachusetts Institute of Technology in Cambridge, Massachusetts.

I have been working in the broad area of atmospheric dynamics since my graduate studies at Harvard. My Ph.D. thesis, *Radiative and photochemical processes in strato- and mesospheric dynamics*, was accepted in 1964. I have since written over 170 papers in the refereed scientific literature, almost all of which dealt with the dynamics of the atmosphere, and over 50 of these papers dealt explicitly with the issues of climate theory and numerical modelling. I have also written or co-written 3 books.

Since 1964, I have been a research associate at the University of Washington and at the University of Oslo, have been a research scientist at the National Center for Atmospheric Research in Boulder, Colorado, have held a professorship at the University of Chicago, have held various endowed chairs and served as director of the Center for Earth and Planetary Physics at Harvard University, and since 1983, have held the Alfred P.

Sloan Professorship of Meteorology at the Massachusetts Institute of Technology. I have received the Meisenger and Charney awards of the American Meteorological Society, and the MacElwane award of the American Geophysical Union. I have been elected a fellow of the American Meteorological Society, the American Geophysical Union, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. I have also been elected to the National Academy of Sciences, the Norwegian Academy of Sciences and Letters, and the Institut Mondial des Science.

I have held distinguished visiting positions at Tel Aviv University, the Hebrew University, the University of Victoria, the Physical Research Laboratory in Ahmedabad, at Kyushu University, and at the Jet Propulsion Laboratory of the California Institute of Technology. I have served on various boards and committees of the National Research Council, and currently serve on the Board on Atmospheric Sciences and Climate. I have been a reviewer and participant in activities of the Intergovernmental Panel on Climate Change ("IPCC"). I have testified on climate before both Senate and House committees.

My research activities over the past 5 years have received over 2 million dollars in federal support. The prime focus of my research has been the development of theories for the earth's climatic behavior, the explanation of major climate changes of the past and the evaluation of the climate's sensitivity to environmental perturbations.

Q.2. What is the purpose of your testimony?

A. The purpose of my testimony is to respond to statements in the testimony of three witnesses concerning the scientific basis for the hypothesis that anthropogenic emissions of carbon dioxide and other so-called "greenhouse gases" will result in a substantial and detrimental change in the earth's climate. The statements to which I respond are contained on pages 2-9 of the testimony of Christopher Davis on behalf of the Department of Public Service, the prepared testimony and supporting report of Peter Ciborowski on behalf of the Minnesota Pollution Control Agency and pages 14-17 of the report attached to the testimony of Stephen Bernow on behalf of the Izaak Walton League, et al.

The import of those statements is that there is a scientific consensus that a doubling of greenhouse gases in the atmosphere as compared with pre-industrial levels will lead to a global average temperature increase of 1.5 to 4.5° C (e.g. Bernow report, p. 16; Ciborowski testimony, p. 2; Davis testimony, p. 6), with potentially disastrous effects, including substantial sea level rise from the melting of the polar ice caps and thermal expansion of the oceans, increased climate variability and increased storm intensity and major changes in ecology (e.g., Ciborowski report, pp. 3-4; Bernow report, pp. 16-17; Davis testimony, pp. 6-7).

My testimony will show that there is no such consensus at all. As an initial matter, it is critical to understand that the temperature predictions referred to by Davis, Ciborowski and Bernow are not based on scientific observation. Instead, they are based on the results of computer models - often referred to as General Circulation Models or GCMs - that are highly unreliable both in their failure to correctly predict past climate change, and in the numerous identified errors in the internal operation of these models. Typically, these models attempt to simulate the earth's climate with atmospheric concentrations of greenhouse gases set at pre-industrial and then again at twice pre-industrial levels. The results of these simulations, unfortunately, are sometimes reported as if they are scientific fact. For instance, Davis' testimony on page

6 states that "the Intergovernmental Panel on Climate Change (IPCC) projected in its 1990 and 1992 reports that a doubling of CO2-equivalents will increase the global-mean surface-temperature by 1.5° C to 4.5° C (2.7° F to 8.1° F)." What he really means to say is that the models used by the IPCC made this prediction. Note that in the IPCC Policymakers Summary attached to Mr. Ciborowski's testimony, on page 1, the predictions of future temperature increases are introduced with the following language: "Based on current models, we predict..." The fact that the temperature increase predictions derive from models is stated clearly on page 2 of the report attached to Mr. Ciborowski's testimony, although he fails to refer to the models when referring to predicted temperature increases on page 2 of his testimony.

The problem with the model results is that there are grave problems with the model inputs that make the model outputs of doubtful scientific utility. Many of these problems are cited in the underlying IPCC reports, although unfortunately (see my discussion below) these problems are not discussed in the Policymakers Summary on which at least Mr. Ciborowski evidently relies. We simply do not have a good enough understanding of the dynamics of the earth's climate to develop a model that accurately simulates the dynamics of such climate or the effect on that climate of increasing atmospheric CO_2. My testimony will demonstrate some of the fundamental flaws of these models.

In addition, I will show that the predictions made by these models are inaccurate when compared with actual climatological data; the testimony of Drs. Michaels and Balling will provide more detail on this point. Finally, I will show that the scientific community is well aware of the problems with the models and their predictions and that there is certainly no consensus in the scientific community that there is a demonstrated basis for global warming theory.

Q.3. As an initial matter, is CO_2 in the atmosphere increasing?

A. CO_2 is increasing and is likely to continue to increase as long as emissions don't decrease. The fraction remaining in the atmosphere is, however, likely to diminish as the rate of increase of emissions decreases.

Models currently used (by the IPCC for example) for evaluating the atmospheric concentration of CO_2 resulting from emissions scenarios, when used to calculate concentrations of CO_2 based on past emissions records, have substantially overestimated current concentrations. There are two points at issue. The first is that the IPCC in 1990 used a model with very long chemical time scales for CO_2 (about 200 years) whereas the evidence increasingly supports a shorter time scale (about 45 years) (Heimann, 1991, IPCC, 1994). A chemical time scale is the characteristic time for chemical sources and sinks to come into balance.

The second is that the exponential time scale that characterized increases in emissions from 1800 until 1973 was also about 45 years, but since 1973 this scale has increased to about 150 years (i.e., increases in emissions have slowed down immensely) (Trends, 1993). This implies much slower increases in atmospheric CO_2 than have been used by the IPCC. Observations of atmospheric CO_2 may reflect this, since the rate of increase of atmospheric CO_2 has diminished sharply since 1991.

Data over the next decade will be able to tell us whether this trend is real. If it is, it will constitute strong support for the shorter chemical relaxation time scales, meaning that increases in atmospheric CO_2 will be much less than projected by models, and this greatly reduces the difficulty of stabilizing atmospheric CO_2 in a relatively short time.

Q.4. What is it about CO_2 that causes us to be concerned about its increase?

A. CO_2 absorbs infrared radiation; i.e., CO_2 is a greenhouse gas. Increasing CO_2 thus could theoretically lead to some warming. However, the amount of warming caused solely by the fact that CO_2 absorbs radiation is relatively insignificant because CO_2 by itself is not a major greenhouse gas. By itself, CO_2 accounts for only a minor portion of the overall greenhouse effect. Whether increasing CO_2 will lead to any material warming depends on atmospheric feedbacks. Atmospheric feedbacks refer to the processes in the atmosphere which act to increase or decrease the direct response to increasing CO_2. The former are referred to as positive feedbacks and the latter are referred to as negative feedbacks.

For instance, in the absence of feedbacks (positive or negative) models predict that a doubling of atmospheric CO_2 will result in *equilibrium* warming between 0.2 and 1.2°C. Equilibrium warming refers to the response of the system given enough time for the system to settle down from the perturbation due to the doubling of CO_2. However, the higher of these values involves an implicit feedback from reductions in stratospheric temperatures. Values of only about 0.2-0.3°C correspond to what might be expected from a doubling of CO_2 if there were no feedbacks whatever (Lindzen, 1995b); such small amounts of warming would be undetectable. The consequences of such warming would be *irrelevant* to policy.

Higher values always result from model tendencies to amplify the simple effect of doubling CO_2. These tendencies are referred to as positive feedbacks, and as will be noted later, they are likely to often be model artifacts, that is, creations of the models that are not supported by known physical processes occurring in nature.

Q.5. Is CO_2 the atmosphere's main greenhouse gas?

A. No, water vapor and clouds are the major greenhouse substances. If one accepts the usual claim that the natural greenhouse warming amounts to 33°C, removing all minor greenhouse substances (including CO_2), while retaining water vapor, reduces this only to about 30°C.

However, there are even problems with the claim that natural greenhouse warming amounts to 33°C. It requires that one ignore the infrared properties of clouds while continuing to require that clouds reflect sunlight. If one simply removed clouds and greenhouse gases, the earth would only be about 15°C cooler.

Crudely speaking, a doubling of CO_2 unaccompanied by stratospheric cooling (see question 4) would change tropopause level fluxes (generally referred to as radiative forcing - the process which produces warming) by about 1.5 Wm^{-2} (watts per square meter). Allowing for stratospheric cooling (a positive feedback) increases this to about 4 Wm^{-2}. By comparison, the flux changes by about 1 Wm^{-2} for every 1% change in relative humidity above a height of 3 km (Thompson and Warren, 1982). It must be noted that our measurements of upper tropospheric water vapor are uncertain to more than 10% (Elliot and Gaffen, 1991) which corresponds to an uncertainty in radiative forcing of about 10 Wm^{-2}. Such uncertainty is far greater than the change in radiative forcing that is due to either past increases in CO_2 or even to a quintupling of CO_2. Given that our uncertainty with respect to upper tropospheric water vapor is so large relative to the greenhouse effect of CO2, we are not even in a position to say that increases in atmospheric CO2 are causing any enhanced greenhouse effect at all.

Q.6. Are model predictions of pronounced warming simply the result of CO_2's contribution to the greenhouse effect?

A. No. As noted, model predictions of equilibrium warming from a doubling of CO_2 in excess of about 0.3°C require that the climate system amplify perturbations (i.e., have positive feedbacks). There are two such major feedbacks, and the models are currently unable to simulate either one.

The main feedback in current models is virtually never mentioned. It arises from the fact that in current models, temperature in the troposphere tends to be vertically rigid (i.e., temperature changes tend to occur uniformly with height below the tropopause; the tropopause level varies from 8 km in the arctic to 16 km at the equator), while temperatures above the tropopause are free to change independently of temperatures below. Increased CO_2 leads to cooling above the tropopause which requires warming below the tropopause (Lindzen, 1995b, IPCC, 1990). Physically, the response could consist simply in a slight warming just below the tropopause; however, the model rigidity forces a surface response as well. This degree of rigidity is not consistent with observations which show that temperatures at different levels can vary independently (Lee and Mak, 1994). Thus, the models are causing a surface response - an increase of surface temperature because of increasing atmospheric CO_2 - at least in part as a result of processes that do not exist in nature. Such discrepancies are characteristic of computational problems in the models.

The other major feedback (in current models) arises from water vapor above 2-3 km (Shine and Sinha, 1991), which I will discuss below. Remaining feedbacks in current models are smaller by a factor of two or more. These feedbacks include those due to clouds and snow/ice reflectivity. Although these appear as positive feedbacks in most current models, they are also highly uncertain in nature even with respect to sign, that is whether they are positive or negative.

Q.7. Is the water vapor feedback soundly established?

A. No. Current climate GCMs are incapable of dealing with upper level water vapor for both computational reasons (they have insufficient vertical resolution for tracking water vapor which varies in density by a factor of about 1000 between the ground and 10 km in altitude) and because they lack the relevant physics. All current predictions of equilibrium sensitivity to doubled CO_2 in excess of 1°C are model artifacts insofar as they depend on the water vapor feedback. The models lack the fundamental process supplying water vapor to the upper troposphere - namely detrainment of ice by deep clouds and the subsequent reevaporation of falling precipitation (Sun and Lindzen, 1993).

This may seem technical, but the current situation is equivalent to solving an equation that is missing crucial terms. The equation can still be solved, but the solution is meaningless.

There are scientists who have argued that they have no reason to question model behavior regardless of the above problems. However, there is simply no question that the dominant physical processes are absent from the models. Models have been shown to severely misrepresent present water vapor and its variations to an extent much greater than the uncertainty in the measurements of water itself (Schmetz and van de Berg, 1994, Chou, 1994, Sun and Oort, 1994). As noted in question 5, the uncertainty in observations of water vapor imply an uncertainty of about $10Wm^{-2}$ in greenhouse warming; model errors in water vapor increase this uncertainty by about a factor of two. By way of comparison, the expected greenhouse forcing from a doubling of CO_2 is between 1.5 and 4 Wm^{-2}.

There is no reason whatever, to suppose that models will magically do better for long-term predictions than they do in predicting current observations. Recent analyses of models and data at the Geophysical Fluid Dynamics Laboratory at Princeton University clearly demonstrate that water vapor in models has a much higher vertical correlation (0.85) than is observed in the data (0.15) (Sun and Held, 1995). *This strongly implies the presence of spurious vertical diffusion in the models which is so strong as to dominate their behavior and invalidate their predictions for climate sensitivity.* The whole issue of uncertainty and error in measuring and modelling water vapor was discussed in a recent meeting of the world's specialists in this area. The results are summarized in Elliot and Gaffen (1995).

In sum, even though atmospheric feedbacks account for most of the warming predicted by the models, those feedbacks cannot be accurately simulated by the models.

Q.8. Is it possible or probable that the feedbacks in nature are negative rather than positive?

A. It is most certainly possible. Indeed, almost all natural surviving systems are characterized by strong negative feedbacks which act to stabilize the system against perturbations. In the case of the earth's climate system, there is ample evidence for the existence of stabilizing feedbacks. Most notably, the zonally averaged equatorial temperature seems to have stayed close to its present value over many millions of years despite major changes in CO_2 levels and changes in solar output (Barron, 1987, CLIMAP, 1976). This stability seems to have extended over both ice ages and equable (i.e., warm) climates. This implies that there exists a very strong negative feedback operating in the tropics, and that major changes of climate in the past involved important changes in the geographical distribution of heating. Such changes appear to have been provided by a variety of factors including changing snow cover, changing orbital configurations, and changing distributions of land and sea (Imbrie and Imbrie, 1980). Simply increasing CO_2 does not provide such a change in geographic distribution, and, given the tropical stability, changing CO_2 is unlikely to produce major climate changes.

It should be noted, in this regard, that current GCMs predict large changes in equatorial temperatures in contradiction to data. Moreover, current GCMs which have attempted to simulate past climate change by altering CO_2 levels in the models, have failed to simulate the major feature of past climate change:

namely the changed equator-to-pole temperature difference (Barron and Washington, 1982). The overall implication of this is that the climate system, like other natural systems, does indeed have negative feedbacks, but that GCMs have thus far failed to replicate them.

Q.9. Does the above exhaust the list of severe model defects?

A. By no means. It has long been noted (Lindzen, 1990) that errors in model dynamic transports (that is to say, the heat carried by atmospheric motions from low equatorial latitudes to high latitudes) make it impossible for models to calculate the present temperature of the earth without arbitrary adjustments in solar constant and/or terrestrial reflectivity. These errors are roughly equivalent to changes in radiative forcing of about 25 Wm^{-2} (Gleckler et al, 1994) compared to the 1.5-4 Wm^{-2} expected from a doubling of CO_2. The resulting adjustments are obviously inconsistent with the natural world, but without them the models predict patently absurd results.

Moreover, coupled models of the atmosphere and the oceans display totally spurious climatic drift (that is to say, the temperatures in models continue changing regardless of climatic forcing) which needs to be 'corrected' by adjusting the heat fluxes between the ocean and the air. Unfortunately, there is no physical basis for the resulting adjustment - except that again without it the model predictions are patently absurd.

As noted by Nakamura et al (1994) and reported in Science (Kerr, 1994), these and other model 'fudges' cannot be used without introducing further problems. Moreover, the 'fudges' are quite substantial, amounting to as much as 100 Wm^{-2}: they are much larger than the 1.5-4 Wm^{-2} expected from a doubling of CO_2! Large numerical models allow for huge numbers of 'adjustments', and the above hardly exhaust those which arbitrarily misrepresent major known processes. There, of course, undoubtedly remain problems that we are not aware of. However, those that have been definitely identified are more than large enough to make predictions of the effect of such small perturbations as those that would arise from a doubling or quadrupling of CO_2 totally unreliable.

Q.10. What is needed for models to correctly predict the magnitude of greenhouse warming? To what extent are these requirements met in current models?

A. Stated broadly, models must include all the relevant physics at a high level of accuracy, and furthermore introduce sufficiently little computational inaccuracy so as not to compromise the physics. These are, of course, difficult, if not impossible, requirements.

In terms of our present knowledge, we know that this means that we must include at least the physics of clouds and water vapor, the dynamics and thermodynamics of the ocean, and the ability to accurately track a quantity, potential vorticity, which provides the restoring force (i.e., the basic springiness) for the waves and eddies that provide the regional variations in climate and the transport of heat in the atmosphere (Lindzen, 1990, 1993, Lindzen and Hou, 1988, Hou and Lindzen, 1992, Hou, 1993, Chang, 1995). Moreover, water vapor and potential vorticity vary greatly over very short vertical scales, and require vertical resolution on the order of 500 m for their proper mathematical depiction. The interface between tropical and extratropical circulation systems also occupies a very narrow region, and the tropical circulation itself depends markedly on small horizontal displacements of thermal features. This implies the need for horizontal resolutions on the order of a degree of latitude or less. Current models fall far short of the needed resolution.

Current models, moreover, are lacking the basic physics of the water vapor budget and of clouds. Indeed, aspects of the physics are still not known. Inevitably, there are elements of the physics which may prove important that are currently unknown, but we are still at the stage where we have inadequately dealt with what is known.

In sum, the models used to support predictions of global warming from increased levels of greenhouse gases suffer serious flaws. Until these flaws can be corrected - until we have a much better understanding of global climatological systems - the model predictions remain highly unreliable.

Q.11. Are model descriptions of what has happened over the past century supported by observations?

A. No. The testimony of Drs. Balling and Michaels explore the answer to this question in more depth. I wish to note here that it is stated by the IPCC Policymakers Summary (IPCC 1992) attached to Mr. Ciborowski's testimony that the observed record is broadly consistent with predictions of equilibrium response to a doubling of CO_2 of from 1.5 to 4°C. Atmospheric CO_2 equivalent gases are now at a level that is almost 50% higher than pre-industrial levels, meaning that as of today we are almost halfway to the doubling of CO_2 equivalent gases used in model predictions.

Given that we are almost halfway to a doubling of CO_2 equivalent gases, one would expect that we should be halfway to the 1.5 to 4° C temperature increase predicted by the models. The ocean delay of the response to perturbed greenhouse forcing (the fact that it takes a great deal of heat to change the oceanic temperature introduces a delay in the onset of warming) might reduce this to about 1°C. But clearly, we are not even at this level of warming. The record for global mean temperature shows a warming of 0.45+/-0.15°C only since 1890, and as shown in Dr. Balling's testimony most of this warming took place before the major build-up of atmospheric CO_2 began after 1940. Since 1940, the amount of warming is relatively insubstantial. Thus, there is no meaningful consistency between the temperature records and model predictions.

The claim of 'broad consistency' depends on very long ocean delays of climate change (ca 160 years to reach 2/3 of equilibrium value), together with the unknown effects of natural variability. In other words, it is sometimes argued that due to the ocean and other factors, there is a long delay between the build-up of

CO_2 in the atmosphere and actual temperature increases. For such long delays, however, it is equally true to say that the observed record is 'consistent' with predictions of equilibrium response to a doubling of CO_2 of from less than *zero to 4°C!* The point is that the claim of 'broad consistency' is simply a claim that large natural variability might have accounted for the difference between observations and predictions; variability of the magnitude used by the IPCC allows for 'broad consistency' with a wide variety of predictions.

However, to the extent there is not a long delay between increased CO_2 and temperature increases, the model predictions are plainly inconsistent with the observed record. It is important to note that ocean delay is not only due to the oceans, but also to their coupling to the atmosphere. The latter is inversely proportional to the positive feedback in the climate system (i.e., large feedbacks are associated with long delays, while small or negative feedbacks are associated with short delays, Hansen et al, 1983). Evidence from climatic responses to volcanos suggests very short delays (Lindzen, 1995a). If these delays are indeed short, then model results are significantly *incompatible* with observations. In fact, nothing in the observational record thus far can be distinguished from natural variability (IPCC, 1990).

Q.12. Is it possible that the predicted greenhouse warming was canceled or delayed by the cooling effect of sulfate aerosols stemming from anthropogenic emissions of sulfur oxides?

A. Unlikely, as shown in more depth by the testimony of Dr. Michaels. It was argued by Charlson et al (1992) that sulfate aerosols resulting from industrial activity would act to reflect sunlight, and thus produce some measure of cooling. The claimed uncertainty was stated to be about a factor of ten. Subject to this great uncertainty, it was estimated that sulfate aerosols could offset about half of the warming due to increasing minor greenhouse gases thus far. However, the lifetime for aerosols employed was about double what is commonly expected from acid rain studies (Seinfeld, 1986). Using the longer lifetimes leads to sulfate values over the North Atlantic comparable to what is found in the Ohio basin. Moreover, according to Kiehl and Briegleb (1993), the scattering calculations of Charlson et al (1992) exaggerate reflectivity by a factor of about 3. The effect is thus reduced to less than 10% of the expected present effect of minor greenhouse gases. It is of course marginally possible that the newer calculations are also in error, but it seems unlikely that the effect will actually be significant. It may be argued that sulfate aerosols might nonetheless be important regionally. However, this is not the issue. Moreover, regional temperatures are not primarily determined by local radiative budgets.

Q.13. Are predictions that the earth will warm about 2.5°C by 2100 simply a consequence of a doubling of CO_2?

A. No. Predictions of 2.5°C warming by 2100 require doubling of effective CO_2 by 2030, and quadrupling by 2100. Given the long ocean delay in current models, a simple doubling of CO_2 levels would produce model warming of less than about 1.5°C by 2100 - even with large and dubious model feedbacks (Lindzen, 1993).

Q.14. Do records of CO_2 and temperature from the past 130,000 years support the theory that increasing CO_2 will cause substantial warming?

A. No. A frequently reproduced set of curves derived from the Vostock ice core (Barnola et al, 1987) do show that CO_2 levels during the glacial period from about 100,000 years ago until about 12,000 years ago was characterized by lower values of CO_2 (about 200 ppm) than were characteristic of the warmer periods before and after the glacial period. It is worth noting that this is about the same percentage difference from 'normal' preindustrial values as are present values. Moreover, when other minor greenhouse gases are considered, we may very well be further from preindustrial values than was the ice age climate.

On the face of it, this would seem to suggest that the changes in ice age CO_2 were only a minor factor in a major climate change. The Vostock data supports this interpretation. The data shows that the onset of the last glacial episode preceded the decrease in CO_2 by thousands of years. That is to say, the change in CO_2 could not have been the cause of climate change.

Moreover, on time scales shorter than 100,000 years, the correlation between climate changes and CO_2 is, in fact, rather poor. Recent data, moreover, have shown the existence of cool periods in the past without accompanying changes in CO_2 (Hodell and Kennett, 1986).

Q.15. Why do we regard changes of 2-4°C in global mean temperature to be important?

A. On the face of it, such changes are relatively small compared to temperature changes each of us deals with due to variations in weather, daily variations, and changing seasons. Thus, it might appear that we could deal with them rather easily. It is, however, suggested that small changes in global mean temperatures are automatically associated with larger regional changes. No such correlation is found in the record of the past century; this is dealt with in detail in question 20. It is also argued that these small changes in global means are historically major, since changes between ice ages and the present only involved changes in global mean temperature of about 5°C.

Such analogies assume that the major changes in climate were consequences of changes in the mean temperature. However, the opposite is likely to be true. Major climate changes of the past were associated with almost no changes in equatorial ocean surface temperatures, but with major changes in the equator-to-pole temperature difference (Hoffert and Covey, 1992). The changes in global mean temperature were the small residuals of these major factors rather than the cause.

Changes in the equator-to-pole temperature difference call for changes in the geographic distribution of heating rather than changes in the net amount. (This is tantamount to stating the fact that fluid flow depends on gradients in pressure rather than the mean pressure.) Moreover, the constancy of equatorial temperatures severely restricts the ability of gross changes in global radiation (as are produced by increasing CO_2) to alter even mean temperatures. It must be added that current GCMs fail to replicate the near constancy of equatorial temperatures (MacCracken and Luther, 1991). This is part of the whole issue of model inability to deal with the regional aspects of climate. Finally, it is sometimes argued that modest warming will lead to major changes in sea level and desertification. We address these matters in subsequent questions.

Q.16. Is there any basis for supposing a warmer world will have increased desertification and droughts, as suggested in the testimony of Davis, p. 7?

A. This is sometimes asserted as a consequence of warming. The idea is that increased warmth leads to greater evaporation of surface moisture. However, increased evaporation, in turn, must be balanced by increased precipitation. Indeed, since 70% of the earth's surface is covered by water, it is inevitable that a warmer climate will have more total global precipitation (IPCC, 1990). However, none of this tells us whether any particular region might become desertified. Data from past climates is fairly unambiguous on this matter.

During the last major ice age, Africa was almost totally desertified, while during the mid-holocene warm period of about 6000 years ago, deserts almost disappeared from Africa (Nicholson, 1989). Similar results are found for the rest of the globe with the exception of a small portion of the northwest of South America where there appear to have been drier conditions during the mid-holocene warm period. On the whole, however, the data suggests that warmer climate is associated with reduced rather than increased desertification.

Q.17. Is there any basis for supposing that warming will be associated with rising sea-level, as suggested in the testimony of Mr. Ciborowski, Report, p. 3, Dr. Bernow, Report, p. 16, and Mr. Davis, pp. 6-7?

A. There is no basis to claim that there will be any significant sea-level rise, and the notion that there will be a "collapse of major polar ice sheets" (Ciborowski, report, p. 3), is preposterous. In fact, if there is substantial warming the result may actually be a reduction in sea levels.

Before continuing with this topic, it is essential to recognize that the claims of major sea level rise that accompanied catastrophic predictions 5 years ago and which seem to be included in Dr. Bernow's and Mr.

Ciborowski's testimony have been rejected by all sides. Assuming major warming (a poor assumption), IPCC estimates are now on the order of a foot or less over the next century, with open recognition that the real effect could even be sea level reduction due to this factor. It is important to stress 'this factor', because climate change is not the major source of sea level change during the past century; nor is it anticipated to be the major cause over the next century. It must be noted that sea level change at any point is dependent on the relative levels of land and sea, and the major factor in such changes is currently the tectonic motions of the land (Emery and Aubry, 1991). Land usage is also an issue: the construction of Laguardia Airport in New York effected a local sea level rise of over a foot.

Returning to the effect of warming, the IPCC guess of a foot or less of sea level rise based on major warming is based on the theory that warming will lead to thermal expansion of the oceans. The advance or retreat of sea ice has no effect on sea level. Under all scenarios for the next century, the major ice sheets (Antarctica and Greenland) will remain below freezing and in this respect Dr. Bernow's (report, p. 16) and Mr. Ciborowski's (report, p. 3) speculation on the melting of polar ice is incorrect. Under such circumstances, increased warming should actually lead to increased snowfall and accumulation on these sheets, and the sequestration of water in these sheets should lead to a reduction of sea level.

Q.18. Is there any basis for supposing that warming would be accompanied by increased storminess and climate variability, as set forth in Dr. Bernow's testimony (report, p. 16)?

A. No. This suggestion appears to have arisen from a note (Emanuel, 1987) wherein it was argued that if tropical surface temperatures increased, while atmospheric temperatures remained unchanged, then hurricanes could reach a larger intensity. It was subsequently noted that all predictions of warming due to increased CO_2 would lead to greater warming in the atmosphere than at the surface.

However, under these circumstances, there might actually be weaker hurricanes. A recent review of this matter by the world's leading experts in the subject (Lighthill et al, 1994) concluded that there was no basis for expecting that warming would lead to significant changes in tropical cyclones, pointing out that the effects of surface temperature would constitute small perturbations compared to more important factors. Nevertheless, this simplistic and incorrect suggestion has been expanded in popular expositions to a prediction of increased storminess and variability everywhere. In the extratropics, such a prediction goes against the basic physics as it is known to operate. Variability in the extratropics is associated with the equator-to-pole temperature difference. Cold spells are associated with the advection by prevailing winds of polar air, while warm spells are associated with the advection of tropical air. Historically, warmer climates have been associated with reduced equator-to-pole temperature differences, and must, hence, lead to reduced extratropical variability.

Q.19. Can science rule out the possibility of important consequences from increasing CO_2?

A. Science is not capable of absolutely ruling things out. However, it is crucial to distinguish between ignorance and uncertainty. When ignorance is at issue, then one is no longer in any position to state whether any proposed action will lead to exacerbation or mitigation of any condition. This is the situation with climate. Although there is a general agreement that substantial increases in CO_2 will lead to some warming, there is no evidence that this warming will be at a level that can be discerned. Moreover, there is no reason to suppose that small (or even large) levels of warming will lead to more severe weather or other negative conditions, and there is substantial reason to suppose that it will be beneficial. This is equally the case for increases in CO_2 itself, because of CO_2's role as a fertilizer.

Q.20. Are regional temperatures closely related to global mean temperature?

A. Over the past century, the instrumental record shows that interannual variations in regional temperatures (such as those in the United States or, more specifically, Minnesota) are far larger than variations in global mean temperature, because much of the regional variation tends to cancel other regional variations when averaged over the globe. The correlation of regional variation with global variation is, therefore, small over the past century (Grotch, 1988). Indeed, it has been argued by Palmer (1993) that global changes are likely to be residuals of the naturally occurring regional variations. Similar arguments have been presented in Question 15 concerning the major changes in climate of the past.

Q.21. Does the scientific community consider the issue of global warming to be essentially settled? If not, what is it doing?

A. No. Clearly, if the issue were 'settled' there would be no major research efforts. Indeed, extensive model intercomparisons show model variations that greatly exceed effects from doubling CO_2 even though models differ more from nature than they do from each other (Boer et al, 1992, Randall et al, 1992, Cess et al, 1990). Efforts are currently under way to discover exactly why models have predicted what they did. Efforts are under way to measure the behavior of upper level water vapor and determine the physics relevant to it. Efforts are under way to improve the computational accuracy of models, and to couple the atmosphere and oceans. Efforts are also under way to understand the major climate changes of the past in order to obtain some understanding of how the climate system actually operates. There is a general understanding that current models are inadequate to this task, but the solution to the problem will call for ideas as well as improved models and data.

Q.22. The testimony of Bernow, Davis and Ciborowski rely heavily on the work of the IPCC, and you have referred to the IPCC predictions in your testimony. What is the IPCC and who participates in it?

A. The IPCC (Intergovernmental Panel on Climate Change) was formed in 1988 by the World Meteorological Organization (an agency of the United Nations) and the United Nations Environmental Program in order to forge a consensus on climate change. The politicized nature of the process has recently been described in Nature (Boehmer-Christiansen, 1994). The IPCC assembles various interested parties to prepare reports on the current state of climate studies. The participants include representatives of environmental advocacy groups, some industry representatives, and government representatives. There are few university scientists who actively participate. Participation involves attending a series of frequent meetings all over the earth. Such participation is hardly compatible with active scientific research. I myself am an IPCC "reviewer," meaning I review and offer comments on the work of a committee of "authors" on certain sections of the report.

Q.23. Are the IPCC reports research documents?

A. No. They are committee reports of the current state of climate science. Strong pressures are exerted to produce 'consensus' statements. However, the documents, themselves, reveal substantial uncertainty, with the later documents (IPCC 1992, 1994) indicating far more uncertainty than the first document (IPCC 1990). The documents are introduced by Policymakers Summaries (as noted, it is the 1992 IPCC Policymakers Summary which is attached to Mr. Ciborowski's testimony, rather than the underlying report itself) severely misrepresent the reports themselves. The head of the IPCC, Bert Bolin, publicly admitted that the summaries were significantly influenced by advocacy groups like Greenpeace (Jones, 1993). The editor of the WGI report, John Houghton, reveals in a recent book that he was motivated by a religious need to oppose materialism (Houghton, 1994). Not surprisingly, most claims concerning IPCC conclusions are based on the summaries rather than the texts. Even so, Boehmer-Christiansen (1994) refers to the summaries as "skilful exercises in scientific ambiguity" using "language which simultaneously allowed Greenpeace to call for a target of reducing emissions by 60 per cent, and the UK Treasury to conclude that no action was needed until more scientific certainty was available - each citing the same source."

Q.24. Are the IPCC reports subject to normal peer review?

A. No. Normal scientific peer review consists in a neutral editor obtaining the comments of scientists, and requiring that the authors respond satisfactorily to criticisms. The IPCC procedure consists simply in the authors asking other scientists to read their statements, and the authors deciding unilaterally as to whether to pay any attention to criticism while providing no response to reviewers.

Q.25. Are the IPCC reports considered to be authoritative within the scientific community?

A. No. Professional scientific discourse generally refers to the reviewed literature. However, the IPCC documents are useful summaries and collections in some cases, and they include many references.

Q.26. Are the IPCC reports consistent with your testimony?

A. By and large, the texts (especially the 1994 update) are, though the IPCC reports often include a variety of sometimes contradictory positions. However, the Policymakers Summaries do make statements contradictory to my testimony. For example the Policymakers Summary of 1990 claimed that there was absolute certainty about the water vapor feedback (contrary to the text which claimed it was a major problem area). In later reports the claim of certainty was dropped, and in the currently available versions of the 1994 Update, it is clearly admitted that we are not in a position to translate changes in minor greenhouse gases (like CO_2) into measures of climate change.

Q.27. Is there a consensus view in the scientific community that anthropogenic emissions of CO_2 and other greenhouse gases will lead to a deleterious global warming?

A. No. To the extent there is a consensus among climatologists on this issue it is that no conclusions can be drawn at this point and that the matter needs more study. My own view is that further research will show that deleterious impacts from CO_2 emissions are highly unlikely. CO_2 is a minor greenhouse gas which is not likely to have a major impact on climate.

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BALLING

BEFORE THE MINNESOTA PUBLIC UTILITIES COMMISSION

In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minn. 1993, Chapter 356, Section 3	))))	Docket No. E-999/CI-93-583

REBUTTAL TESTIMONY OF DR. ROBERT C. BALLING, JR.

Sponsored By:

Western Fuels Association, Inc.
Lignite Energy Council
Center for Energy and Economic Development
State of North Dakota

March 15, 1995

REBUTTAL TESTIMONY OF DR. ROBERT C. BALLING

Q. State your name and briefly review your qualifications.

A. My name is Robert C. Balling, Jr.; I earned a Ph.D. degree from the University of Oklahoma in 1979 and immediately began my career as an assistant professor in the climatology program at the University of Nebraska-Lincoln. In December 1984, I left Nebraska and joined the climate group at Arizona State University where I am now the Director of the Office of Climatology. Over the past five years, I have (a) published 28 articles in the professional refereed scientific literature dealing specifically with the greenhouse effect, (b) published many other articles that deal indirectly with the greenhouse issue, (c) produced a book entitled *THE HEATED DEBATE: Greenhouse Predictions Versus Climate Reality,* (d) generated five book chapters or sections on the greenhouse effect, (e) received over $500,000 in research support for global warming studies, (f) presented approximately 80 invited lectures on the subject in North America, Europe, Australia, Africa, and the Middle East, and (g) served as an advisor on global change issues to the United Nations and the World Meteorological Organization. A copy of my curriculum vitae is attached.

Q. In general, how would you characterize your research on the greenhouse effect?

A. The bulk of the research I have done on this issue deals with how the climate system has responded to a known increase in CO_2 and other greenhouse gases over the past century. Much of this research is empirical-I use historical records of climate to explore how regional, hemispheric, or global systems have responded to increases in greenhouse gases. I believe that this type of research, based on known changes of climate to known changes in the greenhouse gases, could be of substantial value to our policymakers. And basically, much of my research leads to the conclusion that the buildup of greenhouse gases has produced (and will produce) only small changes in the climate system.

Q. To be more specific, describe the increase in greenhouse gases over the past century.

A. Prior to the Industrial Revolution, the amount of atmospheric CO_2 appeared to be near the 275-280 ppm level (the famous Vostok ice core record shows CO_2 concentrations to be 270 ppm about 3,350 years ago and 274.5 ppm approximately 1,700 years ago). However, following that time, anthropogenic emissions of CO_2 have caused a significant increase in atmospheric concentrations of CO_2. Figure 1 shows the rise in atmospheric CO_2 over the past century and a half as determined from analysis of an ice core taken at Siple Station, Antarctica, and direct atmospheric measurements made at Mauna Loa Observatory in Hawaii (Raynaud and Barnola, 1985). The plot shows that atmospheric CO_2 levels have risen 25 percent over the past 145 years (from approximately 282 ppm in 1850 to about 355 ppm today).

Q. Is CO_2 the only anthropo-generated greenhouse gas?

A. No—just as CO_2 has increased in the past century due to human activities, the same is true of methane, nitrous oxide, the chlorofluorocarbons (CFCs), as well as a few other minor greenhouse gases. Methane (CH_4) concentrations were near 0.75 ppm in 1800; however, the recent measurements show methane levels to be near 1.70 ppm, and the increase is related largely to various agricultural activities, most notably, rice paddy agriculture. Nitrous oxide (N_2O) is another naturally-occurring greenhouse gas that has increased in atmospheric concentration due to deforestation, fossil fuel burning, and the use of some fertilizers. Atmospheric concentrations of N_2O have risen from about 285 parts per billion (ppb) for pre-Industrial Revolution levels to approximately 310 ppb in 1990.

Carbon dioxide, methane, and nitrous oxide are greenhouse gases that occur naturally in the atmosphere. Unlike these other greenhouse gases, the pre-Industrial Revolution atmospheric concentrations of the chlorofluorocarbons

(CFCS) were essentially zero. These CFCs are very powerful greenhouse gases, and despite having concentrations that are measured in parts per trillion, the CFCs add significantly to the overall greenhouse effect. These CFCs destroy some ozone in the stratosphere, and because ozone also operates as a greenhouse gas, the destruction of ozone by the CFCs may ultimately minimize the total greenhouse contribution of the CFC molecules (Watson et al., 1990, 1992).

Q. Is there one index that summarizes the build-up of these greenhouse gases?

A. Yes—the overall radiative effects of these many greenhouse gases may be approximated by "equivalent carbon dioxide" values. The resultant value gives an indication of how much CO_2 would be required to produce the same greenhouse effect as other trace gases found in the atmosphere. The equivalent CO_2 values may not be perfect in their representation of the combined effect of the greenhouse gases (see Wang et al., 1991), but in an attempt to simplify this complex situation, the equivalent CO_2 values remain in wide use by climatologists working with the greenhouse effect.

Q. How have equivalent CO_2 levels changed over the past 100 years?

A. Equivalent CO_2 levels were approximately 290 ppm at the beginning of the Industrial Revolution, 310 ppm in 1900, and nearly 440 ppm in 1994 (Figure 1). Since the beginning of the Industrial Revolution, equivalent CO_2 has increased by 50 percent, and in the last 100 years, the increase has been fully 40 percent (see Houghton et al., 1990; Michaels, 1990; Balling, 1992).

Q. Have there been any recent surprises in the buildup of these greenhouse gases?

A. Yes—there has been a tendency to believe that the trends in atmospheric concentrations in these gases would continue without any great surprises into the next century. However, in the late 1980s and early 1990s, the growth rate in the concentration of many greenhouse gases fell well below expected levels. Some greenhouse gases, such as methane and carbon monoxide, have leveled off or even declined (Khalil and Rasmussen, 1994). Other gases, such as CO_2, have shown a substantial reduction in the rate of increase, that is, the atmospheric concentration is still increasing, but the rate of increase is far below previous levels. These findings have surprised many climatologists who are now groping for an explanation. An unusually long-lived El Nino/Southern Oscillation event, a reduction in biomass burning in tropical savannas, the eruption of Mount Pinatubo, enhanced growth in the biosphere, and even major repairs of large pipelines have all been suggested as possible causes of the trends in various greenhouse gases.

Q. Dr. Lindzen testified that "GCM" models are used to predict the climatological impact of doubling equivalent CO_2, and you have testified that equivalent CO_2 has risen by 40% in the last 100 years. How much warming do the models predict for this 40% increase in equivalent CO_2 over the past 100 years.

A. A number of climatologists have discussed the issue of predicted climate response for the changes in equivalent CO_2 observed over the past 100 years (see Houghton et al., 1990; 1992). In general, the models predict a rise in global temperature between 0.5°C and 2.0°C for the change in greenhouse gases of the past century. More specifically, MacCracken (1987) estimated that between 1.1°C and 1.3°C of greenhouse warming should have taken place since the 1850s, while Schneider (1989) listed 1.0°C of expected warming over the past 100 years. Michaels (1990) argued that the existing models imply a greenhouse warming for the last 100 years to be near 1.7°C; he suggests that even the most liberal estimates of the ocean thermal lag (which delays global warming) still leaves the expected warming for the last century to be between 1.0°C and 1.2°C. Wigley and Barnett (1990) also concluded that the expected greenhouse signal of the past 100 years should be between 1.O°C and 2.0°C. Given their estimates of the ocean thermal lag, Jones and Wigley (1990) suggested that we should have witnessed only 0.5°C to 1.3°C of global warming in the past century.

Q. What are the best estimates of global temperature change that has actually occurred over the past century?

A. The most widely used global near-surface air temperature data base is a time series developed by the Climatic Research Unit at the University of East Anglia in Norwich, England (Jones et al., 1986). Figure 2 shows the global temperature plot of this record over the period 1881 to 1993; over this time period, the global temperature record shows a linear increase of 0.54°C.

Q. Are there reliability problems with this global database?

A. Yes—the most significant and widely-recognized problems with the reliability of this global temperature record include the following:

(1) Station relocations produce changes in exposure, elevation, and topography that can change the recorded temperature and create a discontinuity in the record (Mitchell, 1953; Karl and Williams, 1987; Karl et al., 1989). If the station move is well-documented, some of the effects of the relocation can be statistically removed from the record. In addition to potential shifts in the station location, the time of observation may change from one observer to the next and the temperature record is altered. Also, the instruments themselves, along with the recommended exposure to the sun, have changed through time.

(2) The marine air temperature measurements are also prone to similar problems through time. Possibly the most significant problem is that the ships of the world are getting larger, and the thermometers used to measure the air temperature are getting higher above the ocean surface. This change in height, along with other onboard changes, make the marine air temperature records difficult to adjust to some baseline level.

All of these problems influence the long-term temperature record, and despite every effort to remove or minimize their effect, the record remains contaminated with these uncertainties. In addition to these measurement problems, the geographic distribution of the stations and ship records creates yet another difficulty for the "global" temperature record. Some areas of the world are well sampled with the existing network, while other areas are virtually unmeasured. Some of these problems in the record will tend to cancel-out, but they absolutely increase the uncertainty in the 0.54°C trend of the past 113 years.

Q. Are there any other complications in interpreting this warming signal?

A. While each of the problems described above cannot be overlooked in the search for any greenhouse signal, the potential impact on the temperature record caused by the urban heat island effect represents a major contaminant to many of the temperature records. Recognizing that cities tend to warm their local environments, a number of scientists have attempted to explicitly quantify the urban heat island effect in the historical land-based temperature records of the globe (see Karl et al., 1988). A variety of schemes have been used in these analyses, and from this research, it would appear that the Jones et al. (1986) data set has a global urban warming bias somewhere between 0.01°C and 0.10°C per century, with the most likely value near 0.05°C (Jones et al., 1990).

The urban effect creates a localized warming signal that is not representative of the surrounding area. Recently, it has been discovered that overgrazing and desertification may be producing a large-scale warming signal that is clearly not related to the greenhouse gases. The role of desertification in changing the regional temperature was strongly debated following a landmark article by Charney (1975) who suggested that overgrazing in arid and semi-arid lands would increase the albedo (reflectivity) by removing the dark-colored vegetation. The increased albedo would reflect more of the sun's energy, less solar energy would be absorbed by the surface, and surface and air temperatures would drop. Soon after the introduction of the Charney hypothesis, Jackson and Idso (1975) and others argued that removal of vegetation would reduce evapotranspiration rates, less solar energy would be consumed in evaporating and transpiring water, leaving more solar energy to warm the surface and the air. Most empirical data (Balling, 1991; Nasrallah and Balling, 1993) and recent theoretical findings (Franchito and Rao, 1992) support the notion that overgrazing and desertification would act to warm, not cool, the surface and air temperatures.

Because the overgrazing, resultant desertification, and landscape degradation occurs over decades, it is reasonable to expect a relative warming trend for the areas of the earth that have experienced substantial desertification. Balling (1991), Nasrallah and Balling (1993, 1994) have identified warming signals in the Jones et al. (1986) temperature records that appear to be related to this non-greenhouse forcing; the desertification warming signal in the global temperature record, like the urban heat island effect, accounts for between 0.01°C and 0.10°C of the global warming trend of the past century.

Q. Have variations in solar output contributed to the observed global temperature record?

A. Obviously, the total energy output of the sun could play a major role in governing the planetary temperature. For many years, some scientists have argued strongly in favor of this mechanism as a primary control of planetary temperature (e.g., Seitz et al., 1989), while others have rejected the idea that small variations in solar output can explain much of the trend of the past century (Wigley and Raper, 1990). Recently, two researchers have found that the length of the solar sunspot cycle is related strongly to the fluctuations in temperatures on the earth (Friis-Christensen and Lassen, 1991). Although the physical mechanism responsible for the linkage remains elusive, it is noteworthy that over 75% of the observed global warming in this century can be statistically explained by the variations in the length of the solar sunspot cycle.

Q. In summary, how much unexplained warming exists in the global temperature record that may be related to the buildup of greenhouse gases over the past century?

A. The record shows a warming of approximately 0.5°C over the past century, and during that same time, equivalent CO_2 increased by approximately 40 percent. There is a temptation to directly link the two trends. However, as we have seen, urban growth and desertification have certainly contributed to the observed warming. Variations in solar output and volcanism also account for statistically significant portions of the global temperature trend. Although no scientist can say how much warming of the past century was caused by the buildup of greenhouse gases, it seems very likely that the answer is less than 0.5°C. As can be seen, this is substantially less warming than was predicted by the GCM models that are relied on to predict the warming response to a doubling of greenhouse gases.

Q. Has the timing of the warming of the past century been consistent with the build-up of the greenhouse gases?

A. No—the bulk of the warming of the past century occurred in the first half of the record. For example, while the amount of warming from 1881 to 1993 is 0.54°C, the warming during the first half of the record is 0.37°C. Nearly 70 percent of the warming of the entire time period occurred in the first half of the record; the bulk of the greenhouse gas buildup clearly occurred in the second half of the record. Much of the warming of the past century preceded the large increase in greenhouse gas concentrations.

Q. All of the discussion so far has been based on near-surface air temperature; are there other data for representing the global temperature?

A. Yes—one such data set comes from satellite-based measurements of mid-tropospheric temperatures (Spencer and Christy, 1990: Spencer et al., 1990). These temperature measurements are made by a passive microwave sensor system by the 53.74 GHz channel that detects thermal emission of molecular oxygen in the middle and lower troposphere. The measurement is not particularly affected by changes in water vapor, cloud variations, or changes at the surface. In addition, the temperature changes occurring in the stratosphere do not significantly affect the microwave data (Gary and Keihm, 1991). These lower-tropospheric atmospheric temperature measurements are available for 2.5° latitude by 2.5° longitude grid cells on the monthly basis for the period 1979 to the present. When areally-averaged for the world as a whole, the resultant global temperature is accurate to within $\pm$O.Ol°C at the monthly time scale.

Q. What do these satellite data show about the trend in global temperature?

A. A plot of the satellite-based monthly temperatures from January, 1979 to December, 1994 is presented in Figure 3. These data reveal a statistically significant cooling of 0.08°C over the 16-year period. Despite all the talk about global warming during the 1980s and 1990s, and despite the buildup of greenhouse gases during the 1979 to 1994 time period, and despite the anticipated 0.3° per decade warming from the increase in greenhouse gas concentrations, the highly accurate satellite-based global temperature measurements not only show no warming, but they show very real cooling. The eruption of Mount Pinatubo in June 1991 undoubtedly contributed to this cooling pattern; however, Christy and McNider (1994) controlled for such volcanic eruptions as well as El Niño/Southern Oscillation events, and they also found no warming in the satellite-based global temperature measurements.

Q. All of the discussion in your testimony has centered on temperature patterns—are there changes anticipated in moisture levels that may be related to the greenhouse issue?

A. Absolutely—just as all of the models are predicting an increase in temperature for the buildup of greenhouse gases, they also predict increases in cloud cover and precipitation across the globe. Not surprisingly, scientists have been assembling data on these variables and examining trends over the period of historical records.

The global precipitation index (available from the World Meteorological Organization) has been established for over 5,000 stations around the world. The index shows departures from the average based on a 1951 to 1970 "normal" period. As seen in Figure 4, the global precipitation index reveals an upward trend of 16.55 mm over the period 1882 to 1990. In the most broad terms, this general increase in precipitation is consistent with predictions from the models simulations of a doubling of equivalent CO_2.

Given the observed increase in precipitation, one would expect an increase in cloudiness over the past century, and in fact, such an increase has been observed. Results by Henderson-Sellers (1986a, 1986b, 1989), McGuffie and Henderson-Sellers (1988) suggest that global cloudiness has increased between 5 and 10 percent over the past century over land areas; data presented by Warren et al. (1988) and Parungo et al. (1994) also show a total cloud cover increase over the oceans during the past 50 years.

Q. Does this increase in cloud cover impact global temperatures?

A. Yes—detailed studies of the climate record have uncovered a particularly interesting and important pattern in the temperature data: the diurnal temperature range (the difference between the daily maximum and minimum temperatures) has declined significantly over the past half century in many locations around the world (see a review by Karl et al., 1993). The decline in the diurnal temperature range has been well documented in North America using a variety of datasets and analytical procedures (e.g., Karl et al., 1984, 1993; Balling and Idso, 1989; Plantico et al., 1990; Lettenmaier et al., 1994). Similar decreases in the diurnal temperature range have been identified in Europe, Australia, Asia, and Africa (Karl et al., 1993). In order to explain the observed trends in the diurnal temperature range, investigators have proposed many interrelated mechanisms including changes in cloud cover, precipitation, snow cover, atmospheric sulfate levels, and greenhouse gas concentrations (Plantico et al., 1990; Bücher and

Dessens, 1991; Idso and Balling, 1992; Cerveny and Balling, 1992; Karl et al., 1993).

As noted by Michaels and Stooksbury (1992) among others, the trend in the diurnal temperature range is critical in determining the severity of the greenhouse threat. A lower diurnal temperature range would not allow daytime evaporation rates to climb (and would therefore avoid generating the predicted increases in droughts) growing seasons would be longer, plants would experience less thermal stress, and polar melting would be reduced. In many respects, the decrease in the diurnal temperature range could be beneficial to a substantial portion of the global ecosystem. It should be clear that the timing of any temperature change (day verses night) is critical in assessing the impact of the change on other elements of the ecosystem.

Q. Are you suggesting that the greenhouse effect may be beneficial for the planet?

A. What emerges from this discussion is a greenhouse effect of slightly higher temperatures, a reduction in the diurnal temperature range, and an increase in cloudiness and precipitation. This view of the greenhouse effect is consistent with the observational record of the past century and it is reasonably consistent with the model simulation studies, particularly when the climate effects of aerosol sulfates are included in the modeling experiments (e.g., Wigley, 1991; Wigley and Raper, 1992; Box and Trautmann, 1994). However, this view of the greenhouse effect is not consistent with the popularized vision of a global warming catastrophe. Although we rarely hear about greenhouse benefits, it is clear that nighttime warming would lengthen growing seasons, and the lack of warming during the daytime would not force upward potential evaporation rates that could cause an increase in droughts. More clouds and more rain should generally increase soil moisture levels and alleviate moisture stress to plants. No one would argue that all greenhouse effects are bound to be beneficial, but in an environment of thinking only of greenhouse costs, potential benefits must be examined.

Q. Some reports indicate that the greenhouse effect will produce an increase in the frequency and intensity of hurricanes. What is your view of this popular prediction?

A. Like so many elements of the greenhouse scare, there is very little hard scientific evidence to support this prediction. For example, the November, 1994 issue of the *Bulletin of the American Meteorological Society* contains an article entitled "Global Climate Change and Tropical Cyclones" by eight leading scientists in hurricane research (Lighthill et al., 1994). They review the physical principles that govern hurricane activity and conclude that global warming will have little, if any, impact on the frequency and intensity of severe tropical storms. The authors then review work on historical patterns of hurricane activity, and again, they could find no evidence of a statistical linkage between hurricane characteristics and hemispheric temperatures. The authors conclude that any global warming signal in hurricane frequency or intensity should be minor, if existent at all, and virtually undetectable given the high natural variability of hurricane activity. Furthermore, the United Nations Intergovernmental Panel on Climate Change (Houghton et al., 1990) clearly states in their executive summary "climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades."

Q. This Intergovernmental Panel on Climate Change has issued a series of reports regarding the greenhouse issue. Could you comment on your role with the IPCC?

A. I have been involved directly with the IPCC since 1991. I was a contributor and reviewer of the 1992 Working Group I report and I have been a reviewer and contributor to both the 1995 reports forthcoming from Working Groups I and II.

In addition, I am the only American scientist on the United Nations International Panel of Experts on Desertification which works closely with the IPCC. I anticipate further involvement with the IPCC in the immediate future.

Q. Often, we hear that IPCC scientists have reached some consensus regarding global warming. What is your view of this consensus?

A. It is important to set the record straight on these widely cited IPCC documents. Each of the major IPCC reports contains literally hundreds of pages of technical information regarding scientific research conducted around the world. The many climatologists contributing to these reports (myself included) are careful to include results that support and refute the claims of substantial global warming. Virtually any view of global warming finds support in the many IPCC documents. Summaries of the scientific findings regarding what it all means may be crafted to fit an individual's view of the global warming debate. The fact that so many divergent views can be supported by the IPCC is a testament to the quality and comprehensiveness of the material written by the contributors. There is certainly no "consensus" of scientific opinion that emerges from these documents.

For example, against the backdrop of reports of an imminent greenhouse crisis, four fundamental facts are clearly found in the IPCC materials from the climate scientists (Working Group I). One, the numerical models of climate predicting future warming remain crude representations of the climate system—they are simply not up to the task of providing reliable forecasts for policymakers. Two, despite all the claims of massive warming in recent years, the satellite-based global temperature measurements show statistically significant cooling over the past 15 years. Three, the historical climate records of the past century display no trends that are outside of the natural variability of climate. Four, the rate of increase in the atmospheric concentration of many greenhouse gases has slowed, leveled off, or even reversed.

Q. Despite your view of the greenhouse issue, many policymakers are calling for action to reduce greenhouse gas emissions. What is your view of the likely effectiveness of proposed policies?

A. Global warming is almost always presented as an environmental crisis that can be stopped or minimized with appropriate policy actions. Policymakers can debate the impact and the cost-effectiveness of their policies forever, but from a straight climatological perspective, the evidence suggests that realistic policies are likely to have a minimal climatic impact. For example, Figure 5 was derived directly from the 1990 Intergovernmental Panel on Climate Change (IPCC) report (Houghton et al., 1990). The uppermost line represents the IPCC "Business-as-usual" trend in global temperature to the year 2100. According to that scenario, the earth will warm by approximately 4°C over the natural, background planetary temperature by the end of the next century. If that were to occur, many elements of the greenhouse disaster would become reality.

However, if we adopt the IPCC "Scenario B" which includes (a) moving to lower carbon-based fuels, (b) achieving large efficiency increases, (c) controlling carbon monoxide, (d) reversing deforestation, and (e) implementing the Montreal Protocol (dealing with chlorofluorocarbon controls) with full participation, the IPCC projects that the earth would warm according to the line at the bottom of the cross-hatched area. The earth stills warms by nearly 3°C of warming if we adopt the suggested policy. The IPCC "Scenario B" policy spares the earth very little warming (the cross-hatched area) over the entire century; by the year 2050, the policies of this IPCC scenario have spared the earth only 0.3°C of warming. These policies do not stop global warming at all, they barely slow the warming.

Furthermore, the climatic impact of any policy is directly dependent on the amount of warming predicted over the next century. Figure 5 also shows the impact of the IPCC scenario assuming a business-as-usual 1°C temperature increase (this would be much more consistent with the historical record). As seen at the bottom section of that figure, the IPCC "Scenario B" policies spare the planet less than 0.3°C by the year 2100, and by 2050, they would have spared the earth something near 0.07°C. As scientists lower their estimate of temperature rise for the next century, they also reduce the potential climate impact of any corrective policies. In a very recent and important study, Santer et al. (1994) performed a numerical modeling study and concluded that it will take 70 to 100 years to detect any climatic difference between the business-as-usual scenario and the most draconian scenario proposed by the IPCC.

Q. Do you feel that there is a need for immediate action for cutting greenhouse gas emissions?

A. Fortunately, several scientists have seriously evaluated the climate difference between acting immediately and waiting a decade or more to implement selected policies. Schlesinger and Jiang (1991) used a numerical model to simulate the impact of realistic policies hypothetically adopted in 1990, and they calculated the global temperature for the middle of the next century. They then simulated the impact of waiting a decade to implement the same policies, and they found that the temperature of the earth by the middle of the next century was not affected by the delay. Their results obviously generated a tremendous debate in the scientific and policy arenas, but fundamentally, their results continue to support the view that we simply do not need to rush into policy regarding the greenhouse issue.

Q. So in conclusion, what type of global climate change do you think will occur over the next half century?

A. As we have seen in this discussion, we have witnessed a substantial increase in equivalent CO_2 over the past century and the world appears to have become slightly warmer, wetter, and cloudier. These observed changes may simply be a part of the natural variability of the climate system—the buildup of greenhouse gases may have played no role at all in forcing these trends in climate.

Nonetheless, I would expect the planet to continue to warm at a slow rate, possibly warming by another 0.5°C over the next half century. In this scenario, the world would continue to get more cloudy, and precipitation levels would likely continue to rise. Very importantly, these changes have been observed in the past century, and these projected changes are reasonably consistent with the numerical climate models calling for only moderate increases in global temperature. In my opinion, the scientific evidence argues against the existence of any greenhouse crisis, against the notion that realistic policies could achieve any meaningful climatic impact, and against the claim that we must act now if we are to reduce the greenhouse threat.

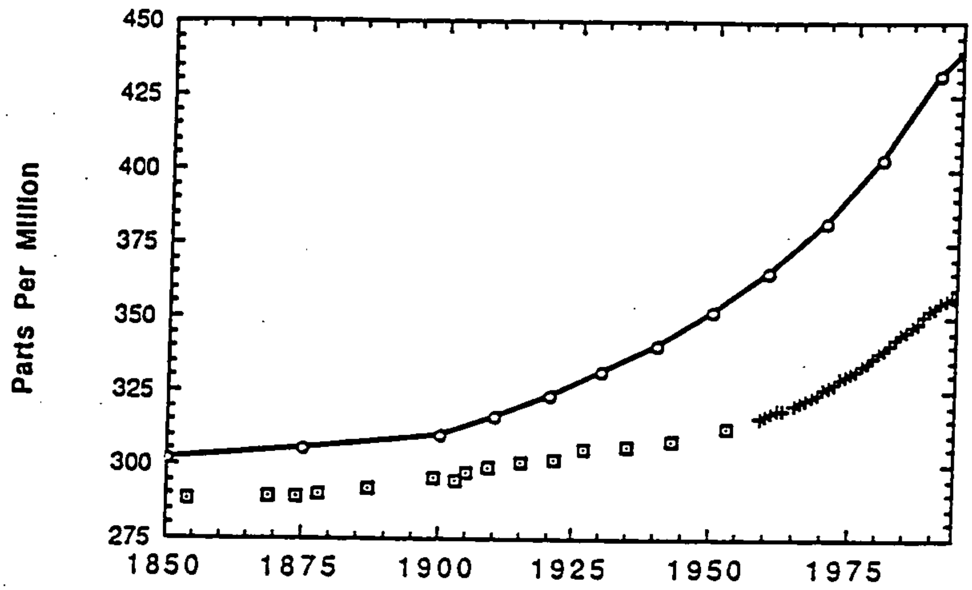

Figure 1. Atmospheric CO_2 concentration derived from Siple Station, Antarctica ice cores (small squares) and Mauna Loa, Hawaii direct atmospheric measurements (plus signs), along with equivalent CO_2 concentrations of all other radiatively-active trace gases acting in concert with CO_2 (open circles). Siple Station data are from Raynaud and Barnola (1985) and Friedli et al. (1986). Mauna Loa data are from Bacastow et al. (1985), Conway et al. (1988), and Thoning et al. (1989). The equivalent CO_2 data came from Houghton et al. (1990), Michaels (1990), and Balling (1992).

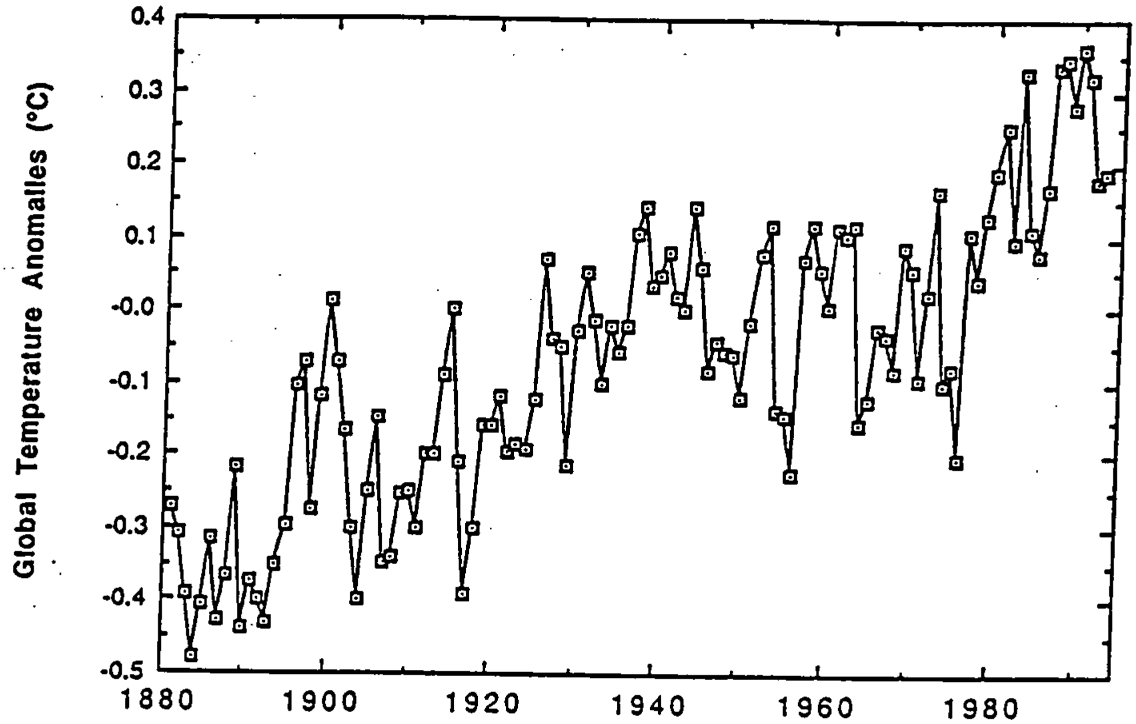

Figure 2. Mean annual global near-surface air temperature anomalies (°C) for the period 1881-1993. Data are updated from Jones et al. (1986).

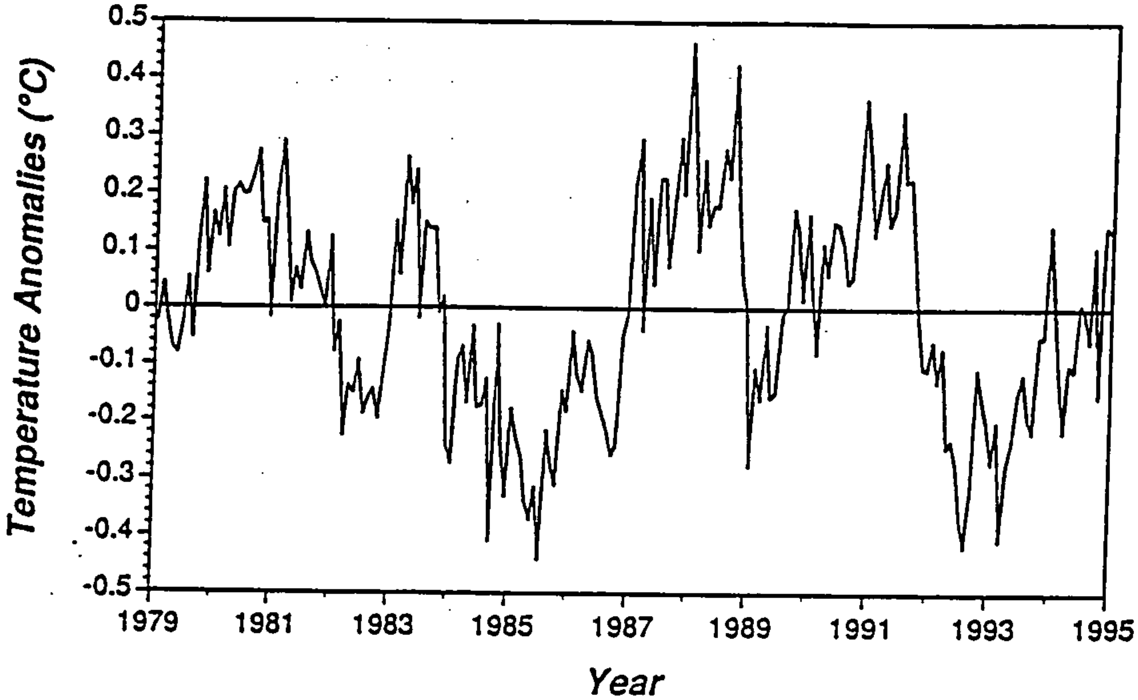

Figure 3. Satellite-based monthly global temperatures for the period January, 1979 to December, 1994; data are updated from Spencer and Christy (1990).

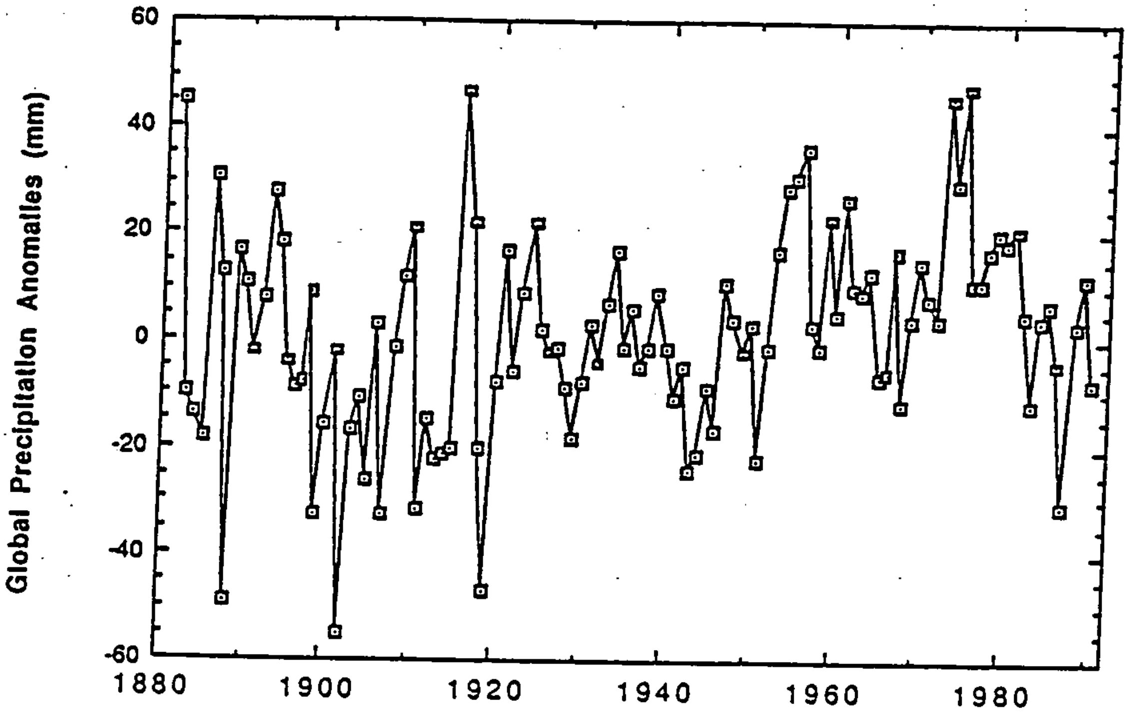

Figure 4. Plot of global precipitation anomalies (mm) from 1882 to 1990; data are available from the World Meteorological Organization.

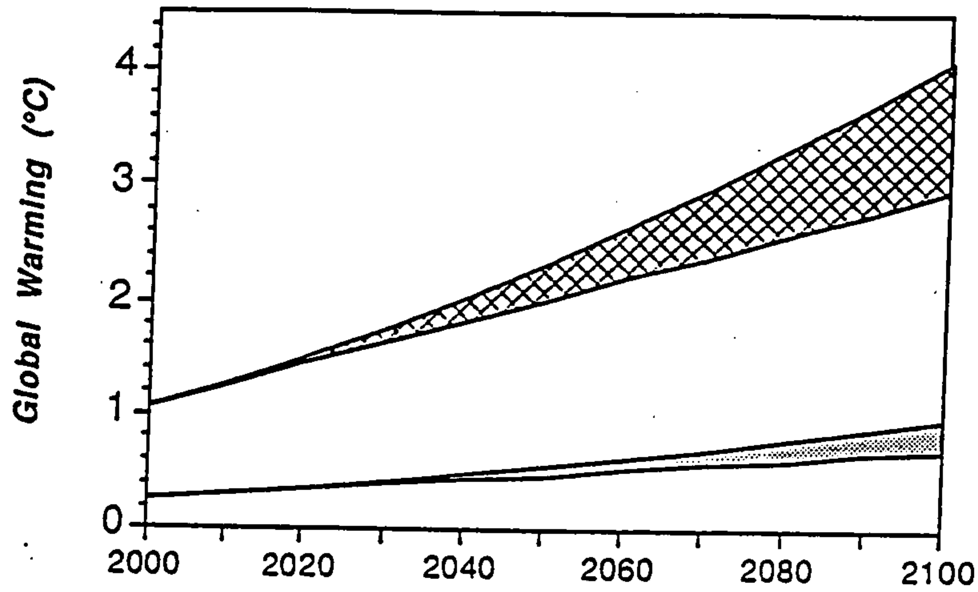

Figure 5. IPCC "Business-as-usual" projected warming (upper boundary of cross-hatched area) and IPCC "Scenario B" projected warming (lower boundary of cross-hatched area) for the coming century (Houghton et al., 1990). The lower set of lines (defining the stippled area) are the proportionally reduced "Business-as-usual" and "Scenario B" estimates.

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