S. HRG. 101-128

CLIMATE SURPRISES

HEARING

BEFORE THE

SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND SPACE

OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION UNITED STATES SENATE

ONE HUNDRED FIRST CONGRESS

FIRST SESSION

ON

POSSIBLE CLIMATE SURPRISES—PREDICTING GREENHOUSE WARNING

MAY 8, 1989

Printed for the use of the
Committee on Commerce, Science, and Transportation

U.S. GOVERNMENT PRINTING OFFICE

99-447 O WASHINGTON : 1989

For sale by the Superintendent of Documents, Congressional Sales Office
U.S. Government Printing Office, Washington, DC 20402

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

ERNEST F. HOLLINGS, South Carolina, *Chairman*

DANIEL K. INOUYE, Hawaii
WENDELL H. FORD, Kentucky
J. JAMES EXON, Nebraska
ALBERT GORE, JR., Tennessee
JOHN D. ROCKEFELLER IV, West Virginia
LLOYD BENTSEN, Texas
JOHN F. KERRY, Massachusetts
JOHN B. BREAUX, Louisiana
RICHARD H. BRYAN, Nevada
CHARLES S. ROBB, Virginia

JOHN C. DANFORTH, Missouri
BOB PACKWOOD, Oregon
LARRY PRESSLER, South Dakota
TED STEVENS, Alaska
ROBERT W. KASTEN, JR., Wisconsin
JOHN McCAIN, Arizona
CONRAD BURNS, Montana
SLADE GORTON, Washington
TRENT LOTT, Mississippi

RALPH B. EVERETT, *Chief Counsel and Staff Director*
WALTER B. MCCORMICK, JR., *Minority Chief Counsel and Staff Director*

SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND SPACE

ALBERT GORE, JR., Tennessee, *Chairman*

JOHN D. ROCKEFELLER IV, West Virginia
LLOYD BENTSEN, Texas
JOHN F. KERRY, Massachusetts
RICHARD H. BRYAN, Nevada
CHARLES S. ROBB, Virginia

LARRY PRESSLER, South Dakota
TED STEVENS, Alaska
ROBERT W. KASTEN, JR., Wisconsin
TRENT LOTT, Mississippi

CONTENTS

LIST OF WITNESSES

CLIMATE SURPRISES

MONDAY, MAY 8, 1989

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND SPACE,
Washington, DC.

The subcommittee met at 9:38 a.m., in room SR-253, Russell Senate Office Building, Hon. Albert Gore, Jr. (chairman of the subcommittee) presiding.

Staff members assigned to this hearing: Mike Nelson, Penny Dalton, professional staff members; and Sherman Joyce, minority staff counsel.

OPENING STATEMENT BY SENATOR GORE

Senator GORE. This hearing will come to order. I would like to welcome all of our witnesses and all of our guests.

We are going to have three panels this morning. We are going to move it along rather quickly. Each witness will be limited to 10 minutes, and questions will be held until the end of each panel, and we will proceed right after an opening statement.

Global warming has moved from a topic confined to scientific journals to the cover stories of the major weekly news magazines. Barely a week goes by without another conference on the changes that humankind is making to the global environment. With increasing precision scientists are documenting the danger now and the risks ahead.

This kind of attention is essential if we are going to address and solve this most critical environmental problem. Global warming is the worst and most urgent environmental crisis the world will face in the next decade and the next century.

Around the globe the public and the policy makers must know and understand the threat we face.

I believe it is unfortunate that this administration actively seeks to censor the scientific evidence concerning global warming and ignore the facts. It is inexcusable and represents a dangerous pattern of environmental fraud that is becoming all too routine.

The promises of environmental activism are being replaced by environmental indifference and, worse, by concerted efforts to discredit the very best researchers, to ignore the very issues emerging with new urgency around the world, and to push the United States into the shadows when we should be in the lead.

Today in Geneva our negotiators on the global warming problem have been instructed to argue against their better judgment that no actions are necessary because we need more study. And yet, today, here in Washington at this hearing when some of those studies they claim to be waiting for start to reach conclusions, they order the scientists to change their best scientific judgment, at least as it is expressed to Congress, and argue that the conclusions are iffy or more iffy than the scientists would like to tell us.

President Bush only months ago told this nation that he was an environmentalist. And yet, in the past few days alone, we have seen his administration back away from a critical diplomatic initiative on global warming. We have seen his administration weaken even his predecessor's recommendations for controls on toxic air pollutants and this morning censor one of our government's foremost scientists, not on questions of policy, but on his scientific opinions concerning detailed, painstaking research.

There are a few environmentalists in this administration such as William Riley at EPA, who is absolutely first rate. But they are outnumbered by the James Watt clones put in key posts elsewhere in the administration.

The environmentalists are being overruled and, worse, they are sometimes being muzzled.

The witness who will lead off our third panel, James Hansen, is one of our nation's leading atmospheric scientists. In fact, that statement can be made about all of the witnesses here this morning.

Dr. Hansen has developed some ground-breaking global climate models to measure the future changes in our climate caused by the buildup of greenhouse gases, changes which could have a dramatic impact on life as we know it today.

These models are critical for policy makers involved in the debate over responses to this serious global challenge. And yet, this administration prefers to abuse Dr. Hansen's credibility and his research to promote a campaign of disinformation with frightening consequences.

How are we as policy makers to develop effective responses if this administration is routinely going to censor the evidence that scientists bring to Congress?

I am not eager to hear Dr. Hansen's formal testimony as it has been edited and altered by those who either do not like what he has discovered or do not want us to know the facts. But we will hear it patiently, and then I am eager to hear what Dr. Hansen and his other colleagues here today have to say independent of the bureaucrats who seem to be scared of the truth.

Scientists tell us that global temperatures could increase two to five degrees Centigrade in our lifetimes because of the billions and billions of tons of carbon dioxide we pump into the air every year and because of emissions of other greenhouse gases like chlorofluorocarbons, methane and nitrous oxide, which will make the problem even worse.

It is because global warming is a long-term problem that many people would rather think about it later. They hear predictions about the year 2050 and assume they do not have to worry yet. What they do not realize is that researchers are predicting that we will see noticeable climate changes in less than 10 or 20 years.

But, let us face it. It sometimes seems easier to ignore the whole problem. Certainly that is what this administration wants to do.

The skeptics use uncertainty as an excuse for inaction and when the uncertainty begins to narrow they step in and say wait a minute. Let us keep it as uncertain as possible because if people get the idea that this problem is real, we will have to do something, and we do not want to do anything. That is the approach they are taking. That is why they are scared of the truth.

It is a dangerous mistake. We cannot afford to ignore this issue. We will be affected by global warming and so will our children and our children's children.

We are here today for a detailed examination of this issue, specifically of global climate models. Our witnesses will discuss how these models work and what they can and cannot predict. We need to understand them if we are to effectively address the problem of global warming.

Predictions of future climate require understanding of two parameters, first, the climate's sensitivity to emissions of greenhouse gases and, second, the amount of greenhouse gases that will be emitted in the future. How the climate responds to CO_2, CFCs and methane emissions is a matter of science. That is what we will focus on today. Now, the other part of the equation, the amount of future emissions, is a matter of policy, just as what we do about them is a matter of policy. Those questions depend less on the laws of physics and more on the laws of Congress and of governments around the world.

There is broad consensus now that there will be global warming. It is just not clear how much. The uncertainty in the models actually should compel us to do more, not less.

It is a little like life insurance. If you were 100 percent sure that you would live to be exactly 87 years old, you would not bother to buy insurance until you were 86. But, in the real world you do not know how long you will live, so you pay the premiums to be prepared. Because of uncertainty, you take action.

It is the same with global warming. We need to be prepared for global warming. We need to take action to reduce it and avoid it.

In addition to understanding the uncertainties in these models, we will examine other aspects of global warming, which have also often been overlooked. The first question everyone asks about global warming is how much. But equally important is how abruptly, how soon.

The early models of global warming indicated that temperatures would go up steadily as carbon dioxide concentrations increased. But more recent, more sophisticated models indicate that there could be some radical fluctuations as the global climate warms.

Some places could be colder as others become warmer, and there are indications in the ancient geological record that climate change sometimes occurs in fits and starts, suddenly. Needless to say, abrupt discontinuous changes in climate could be even harder to adjust to than slow, steady increases in temperature.

These abrupt changes are due in part to the many complicated feedback loops that influence climate. That simply means factors that magnify a gradual change and make it speed up.

For instance, if the climate starts to warm and ocean temperatures increase, the sea ice in the Arctic and Antarctic could start to melt more quickly than elsewhere in the world as the white reflective ice is replaced by dark green ocean, the sunlight reflected from the ice will, instead, be absorbed by the ocean leading to more warming and even less ice. That is a positive feedback loop.

As a result, it is possible that much of the Arctic pack ice could disappear in just a few decades after warming reached a certain point with, of course, major implications not only for Arctic ecosystems, but for global weather patterns.

Such feedback loops are very hard to understand and harder still to incorporate into computer models. So, several of our witnesses will discuss different feedback loops that we need to keep an eye on, ones they have studied, and they will attempt to predict how they will affect future climate.

We need to keep improving the research and refining the predictions. Our witnesses will discuss where work needs to be done and what additional resources are needed.

I have repeatedly called for new attention to this area, for additional supercomputer power for climate modelers so that our climate models will not be limited by a lack of hardware. But researchers will need much more than just bigger and more powerful computers. Better climate predictions will require a better understanding of the entire earth. NASA's Mission to Planet Earth will help greatly in this regard.

At a Commerce Committee meeting early in March Dr. Sally Ride described how much there is to learn about our home planet. She stressed that a global perspective is needed to study global climate change, and that requires satellite observations. She said that we must, in her words, "exploit our space program to explore not only other worlds, but our own as well".

As the authorizing committee for NASA, the National Science Foundation, and NOAA, the Commerce Committee will have much to do with providing researchers with the funding and tools they need to understand global warming, and we will be active within our jurisdiction on the problems and on the solutions—for various aspects of this large problem.

In the months ahead we are going to be addressing these questions in great detail. The threat of global warming is one of the most complicated and challenging problems that researchers and policy makers have ever faced. I am glad that we are able to hold this hearing today and assemble the talent that we are going to hear from today.

We will need good communication, uncensored communication between scientists and policy makers if we are going to address this critical global problem.

We will need an administration unafraid of the facts and unwilling to postpone necessary action.

Before going to the witnesses let me recognize my colleague Senator Bryan.

OPENING STATEMENT BY SENATOR BRYAN

Senator BRYAN. Thank you very much, Mr. Chairman. I would like to congratulate you for your leadership in this area, for the timeliness of our hearing, and for the very distinguished panel that you have assembled here for us this morning.

Senator GORE. Thank you very much.

I have opening statements from Senators Hollings and Pressler that I will include in the record.

[The statements follow:]

OPENING STATEMENT BY THE CHAIRMAN

I want to commend Senator Gore for calling this hearing on predicting greenhouse warming. Global warming is a threat which we must face, and in order to face it we must understand it. Over the past week, however, events have shown us that in the Bush administration, the quest for scientific understanding still takes a back seat to political expediency. The Committee has learned that Dr. James Hansen's testimony for today's hearing was changed to soften his conclusions about the seriousness of the global warming threat which we are facing.

Today's hearing was called in order to get the facts about global warming, which the Congress needs in order to formulate effective policies to address this critical problem. Unfortunately, in recent years, some Administration officials have seemed to have little interest in the facts. We all recall the situation just two years ago when Secretary of Interior Hodel brought up a proposal calling for us to use hats and sunglasses to protect against the danger of ozone depletion. In dismissing the growing evidence that manmade chemicals are destroying the ozone layer, Secretary Hodel ignored a potentially serious and long-term threat to public safety and to the global environment. He also subjected this nation to worldwide ridicule. Finally, and most importantly, his careless denial of the problem threatened to undermine the Montreal Protocol, a very substantial international commitment to dealing with the problem.

I am concerned about Dr. Hansen's experience for two reasons. First, we have indications that such interference from OMB and policy-level bureaucrats in the Administration is not unusual. Too often, the "OMB clearance" process has caused delays in the submission of testimony to the Committee from Federal researchers. It is time for OMB to realize that we need good science if we are to make good policy, and good science requires the free and open discussion of research results. And the science must be independent of the policy. Scientific conclusions must be judged on their scientific merit, not on whether the Administration finds them political palatable.

My second concern is for the scientific credibility of federal researchers, themselves. Some of America's top scientists are working on global change research. They have invested too much effort, and we have invested far too many public dollars to allow their conclusions to be rewritten by politicians and special interest groups. The fate of our nation and, indeed, the continued habitability of our entire planet will rely on what these individuals can find out. It is our responsibility to ensure that their right to speak freely is not fettered because they are public servants.

These are critical times for America and for our fragile planet—critical because the course we set here in Washington and the policies we pursue will have a profound impact on the Americans of tomorrow, their standard of living, and the quality of their lives.

As Chairman of the Commerce Committee, I am committed to providing for the scientific understanding needed to make rational policy decisions. The Commerce Committee has jurisdiction over the National Science Foundation, the National Oceanic and Atmospheric Administration, and NASA, which fund much of this country's global change research. Thus it is this Committee's responsibility to see that our nation's global change research program is well-funded and well-run. We need to see that scientists have the data and tools they need to make meaningful, accurate predictions of how climate will change in the coming decades.

In January, I introduced S. 169, the National Global Change Research Act, which would mandate a 10-year federal government plan to study global environmental change. The bill responds to the need for a determined and coordinated research effort, both here in the United States and worldwide, to get the facts about the exact causes and consequences of global environmental change. Good answers to the pressing questions we face will not come easily, and probably not cheaply. The challenge is enormous, but the skill and tools of our scientists have never been better.

Finally, we must ensure that scientific facts are not dismissed merely because they force us to make uncomfortable political decisions. For the sake of our children and our grandchildren, we must face the consequences of our actions now.

OPENING STATEMENT BY SENATOR PRESSLER

Mr. Chairman, thank you for calling this hearing on the alarming problem of global warming and related global climatic change. Your interest and leadership in this area is well known. I would like to make clear to everyone here, and the distinguished witnesses in particular, that my concern is just as great. Global warming is very likely the most serious problem facing this world in the near future.

As we are aware, global warming is due in large measure to the enormity of our man-made emissions of carbon dioxide and other greenhouse gases. It is the concensus of the scientific community that the so-called greenhouse effect threatens to cause dramatic changes in the world's environment. The current global warming trend, if continued, may well lead to a variety of adverse consequences such as sudden unwelcome changes in the climate, severe droughts, the widespread death of forest trees, and the flooding of coastal areas.

These disturbing possibilities make it imperative that we devise and implement ways of checking the global warming pattern. I am hopeful that this hearing will provide valuable insight into how the various climate models used by scientists work; in what respects they produce different results and why; and what additional research is required to refine and improve the models.

Global climate warming is not a problem unique to any one area of this country. Nor is it just a national problem. It is a worldwide problem. Everyone is affected. In my home state of South Dakota, for instance, rising sea levels are not likely to be a great concern, but drought and the destruction of forests can be devastating.

I feel fortunate that my home state also has something to offer in the effort to understand global warming. I often mention the EROS Data Center in our hearings on global climate change. This Center has processed and archived data from the Landsat satellites for the last fifteen years, providing us with an invaluable base of scientific knowledge for the study of global changes. In the mid-1990s, it will serve as the processing center for NASA's Earth Observing System (EOS), which will provide even more critical information for this effort.

Mr. Chairman, I will close my remarks by saying that I look forward to hearing the testimony of this distinguished group of witnesses to advance our understanding of the global warming phenomenon and facilitate our efforts to learn even more.

Senator GORE. Our first panel will come to the witness table, please. Dr. Stephen Schneider, who is Section Head for Interdisciplinary Climate Systems at the National Center for Atmospheric Research in Boulder, Colorado, and Dallas Peck, who is Director of the U.S. Geological Survey located in Reston, Virginia.

Gentlemen, I want to welcome both of you and give you our deep thanks for getting us off to a good start this morning.

I might say on a personal note that both of these witnesses are personal friends and have done tremendous work for many years in this field, and I am just delighted that you could be here this morning.

We will hear from both of you. Try to limit your presentations to 10 minutes each if you can, and then we will have questions after both of you have concluded.

Dr. Schneider, thank you, too, for playing host along with your colleagues at NCAR to the recent conference on global climate change last November.

In any event, please proceed. Without objection, your prepared remarks will be included in the record in full.

STATEMENT OF DR. STEPHEN H. SCHNEIDER, SECTION HEAD, INTERDISCIPLINARY CLIMATE SYSTEMS SECTION, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, BOULDER, CO, ACCOMPANIED BY DR. DALLAS L. PECK, DIRECTOR, U.S. GEOLOGICAL SURVEY, RESTON, VA

Dr. SCHNEIDER. Thank you very much, Senator. I believe that there is no cord on the projector which I am going to use, so I will just grab this microphone and go there with it.

I thought I would start out the morning by showing a picture that we need to do occasionally when we discuss the term greenhouse effect because as many of you know, in the popular press, the greenhouse effect is a phrase that has become a symbol for the entire syndrome beginning with what people do to change the atmosphere and the environment, how we translate that into future projections from energy and population growth, what that means in terms of climate change, which is the modeling component we will focus on today, whether that is wetter or drier or sea level rises and so forth, what happens to heat waves, whether that is good or bad, whether we should do anything about it and ultimately how.

So, that whole suite of things gets called the greenhouse effect, which obviously is an area with controversy, but the greenhouse effect itself, actually, as a scientific proposition is one with virtually no controversy. It has been established for well over a century in the atmospheric sciences, and this very first slide shows that the amount of energy that comes in from the sun which is in the upper part of that picture, if you break it down into where it goes, about half of it is either reflected or absorbed in the atmosphere, and the other half reaches the earth's surface. Then, that heat is translated into another kind of heat called planetary or infrared radiation which is given off by any object with temperature, and then that infrared radiation is then radiated upward. And here is where the atmosphere does its "greenhouse effect."

And what that means is that it lets through about half the sunlight, but blocks something like 90 percent of the outgoing infrared radiation. Then, the atmosphere reradiates that energy back down to the surface, which is the greenhouse effect, and up to space.

Again, that is not a speculative theory. That has been validated by literally thousands of laboratory experiments and millions and millions of satellite and balloon observations.

The other thing that we know for sure is if you increase the gaseous envelope around the atmosphere by adding gases like carbon dioxide, methane and fluorocarbons and others that you will hear of from other witnesses, that that will increase the heat trapping properties of the atmosphere.

So, that is, again, something that is established essentially beyond doubt, and if anybody reads in the papers that the greenhouse effect is a dubious proposition, they are not talking about heat trapping. They are talking about the details: where it will be wetter and drier and warmer by so much and what to do about it.

Okay, we have disposed of that issue, so let me go on and mention something of the methods which this next slide shows of how we try to forecast the future.

This is a slide that was put together about 12 years ago now, by my colleague William Kellogg, and I show it partly because it was courageous that he had published this back in the 1970s when the earth was apparently cooling, and also partly because it shows the methods that we use and how we apply models and so forth.

What we can see here is the change in temperature of the planet from 1850 (in the left corner) to a projection out to 2050 on the right. And there is a shaded zone which is called the approximate range of undisturbed climate in the past few centuries.

Now, the climate varies of its own accord on the order of a degree Celsius on the time frame of a century or two or on the order of a few tenths of a degree on the time frame of a decade. Those are natural and have not been caused by human pollutants. It has been going on for a long time.

So, what we are interested in, then, is what Will Kellogg showed here by these dots. Sometime between the decade of 1990 and the year 2000, these dots that he sketched in emerged from that shadowy zone, meaning the signal of climate change is then predicted to emerge from the climate noise.

So, this decade is rather an exciting time for climatologists because we are literally performing an experiment on the laboratory we live in. It is not one most of personally would recommend, but since it is out there, we use it to calibrate our understanding of what we are doing.

The other thing that we do to calibrate our understanding is we take a look at the very large changes in the past which Dallas Peck will tell you about, and then we use those to test our theories and then apply those same theories or models to predict the future.

Senator GORE. If we had a choice, you would not recommend that we carry out this experiment, would you?

Dr. SCHNEIDER. No, I would not, but since we are doing it, we might as well understand as much as we can about it as fast as possible because at any stage at which we choose to act, we can always mitigate to some degree change that otherwise would have taken place—and plus the fact that we are already committed to changes we will get to in a minute. And, therefore, if we are going to rationally learn how to adapt to that change, having better insight into what it is makes adaptation easier.

In fact, in a sense, a bottom line conclusion beyond modeling, in my opinion, since we have brought it up now, is simply the faster we change things, the more likely it is that we will be damaged because the faster we change things, the less we can anticipate what the changes are. Therefore, the less ability we will have to adapt to them.

Well, let me proceed, then, to show you that there are error bars, as you can see, and sometime over the next decade we emerge from this noise level if these forecasts are correct, and these bars represent uncertainty of about a factor of two, which Kellogg had built in to show uncertainty in the models. Let me turn next to that question.

Okay. This picture shows a change in temperature from a host of trace gases, carbon dioxide, methane, nitrous oxide, tropospheric ozone, fluorocarbons and so forth.

If you take a look at how much of the current greenhouse effect augmentation from human activities is due to people, it is broken down into about 50 percent of which is due to carbon dioxide which we know beyond doubt has increased on the order of about 25 percent since the industrial revolution.

We also know that methane has nearly doubled and Ralph Cicerone will talk about that later, and there are other gases. You take a number of these trace gases together and add them up, they come out to be almost equal to the carbon dioxide effect.

What this chart shows is a projection into the future where the combination of the greenhouse gases raises temperature about 2 degrees C. Now, that projection has a series of wide bars on it. Those bars from the top to the bottom are not meant to represent the uncertainties in the climate models, but the uncertainties in what people will do and to add greenhouse gases how nature will dispose of these gases.

And to those uncertainties we have to add the uncertainties associated with climate modeling. So, the bars get wider. And, as you said in your opening statement, Senator Gore, that means that it is possible things could be not as warm as we project in the future or even warmer because the sword of uncertainty cuts in two directions, and what we do not know expands in both ways.

Well, let us proceed to what we do know or at least how we try to know.

This is a complicated looking picture, but it makes the point you will hear over and over again in discussing any kind of projection of the future. And this has to do with what we call cloud feedback. I am sure Dr. Ramanathan will talk about it in detail, but let me in my overview briefly sketch it out.

If you begin with an environment, which, over here, I have labeled climate and aerosols and CO_2 and clouds, and you have some present state of the environment, and from that you calculate the amount of radiation from the sun that is absorbed or reflected and the amount of infrared that escapes, you can, essentially, in your model, calculate what the planetary temperature is, the strength of its greenhouse, and so forth.

Now, if you arbitrarily in this model change the amount of greenhouse gases, change the CO_2, methane and so forth, this is going to change the radiation fluxes. What that is going to do is change the heating, changing the densities and the pressures, which, in turn, will give rise to altered motions in the atmosphere, which then give rise to altered motions in the oceans, and so forth. It changes the evaporation patterns.

Well, that, in turn, changes the amount of cloudiness. And cloudiness is critical because brighter clouds over darker soil or water, for example, reflect sunlight and can cool the planet. On the other hand, taller clouds actually get colder tops and can heat the planet. So clouds operate both, on the visible part of the spectrum and on the infrared. And they are the single most critical element in determining the sensitivity of the Earth's temperature to disturbances such as greenhouse gases that we are adding.

And what we learned 20 years ago was that to perhaps a factor of two or three, we could estimate what the change or sensitivity of the Earth's climate is to something like a doubling of CO_2. The typical numbers came out somewhere in the one to three degree celcius warning range about 15 or 20 years ago. Now, most of the more sophisticated models actually are somewhat higher than that range (above 3–5° (warning), but let me focus on why.

So, describing these models was the task you asked me to do. And let me quickly say what is a model. Well, a model is simply a mathematical representation of the atmosphere, oceans and the important components of the climate system, where we describe them by basic physical laws: the conservation of mass and energy and motion, and then an ideal gas law.

The problem is these are impossibly difficult partial differential equations that are all coupled, and nobody knows how, nor, in my opinion, will they know how, to solve them exactly for the foreseeable future. So we have to solve them approximately. And the way we do that is we break up the continuous atmosphere, you know, one blob of air touching the next, into a finite mesh or grid. And then we solve for averages, averages over an area, say, the size of the State of Oregon or Colorado.

Now, I just got through saying that clouds are the single most important element. I am sure none of us have seen a cloud the size of the State of Colorado. So the problem that we have is what we call parameterization, or parametric representation, which is trying to figure out the effects of processes that occur on smaller scales than we can resolve. And we can do this in a way that involves being essentially clever.

For example, we know that the amount of clouds that we have would depend on the relative humidity. If it is a very humid day, it is a better chance that we have cloudiness than if it is a dry day. So we can ask how much humidity is there in the box. Then the question is—can we predict clouds from that—can we validate that?

This is an example of an actual grid from the general circulation model; this is my laboratory's version. And this shows you the resolution that you typically have. Incidentally, to be able to run a model at this particular resolution, which is four and a half degrees in latitude by seven and a half degrees in longitude, takes something on the order of 10 hours of supercomputer time to run one year's climate.

And in order to have reasonable studies in the future, we need to make literally dozens and dozens of such runs over a hundred-year period. So each one is something like 1,000 hours of computer time each, and it is simply not possible with present resources to do those kinds of runs. So what we do is maybe one long run or two in a year at each laboratory and then we try to do shorter runs guessing what things will look like farther along. That is the standard method.

Well, finally, let me conclude by giving some examples of what the models predict. This particular picture, which will be amplified later by Dr. Mahlman in his Panel 3 testimony, shows the Geophysical Fluid Dynamics Laboratory's results for the change in an important variable, soil moisture, in the model.

And the method that is typically used is that we run a control case, we run 20 years of present weather—remember these models generate weather internally—and then we average them up over

20 years. And then we run a doubled CO_2 or some other scenario. And from that, we then compute the perturbed climate. We subtract the control from the perturbed.

And what this shows in red is where it is drier, and in green where it is wetter.

And the first thing that strikes your eyes is substantial changes in soil moisture, some areas wetter, some areas drier.

Now, this is for a fixed amount of CO_2. That is not the way the real world will proceed. We will have a transient increase. So what one cannot do is ever take this kind of a picture literally. But not taking it literally is not equivalent to saying we shouldn't take it seriously. Because what it recommends, and others like it, is that there could be substantial changes on the order of tens of percent differences in soil moisture.

The summer last year, which gathered much press attention as a greenhouse effect—even though, in fact, you could never prove or disprove a greenhouse effect from looking at one warm year or one cold year, you need a long sequence—that summer was typical of what this model had suggested, which is part of the reason that it got so much attention, which is the drier zone in the U.S. and wetter area near India, for example.

So, while that might be statistically something that would come out in the wash in any one year, of course, we cannot ascribe that to greenhouse gases, but nonetheless, those kinds of changes are plausible. Then it is up to us, later on, to ask the next step, does that make any difference?

Senator GORE. If this model is correct, it would lead you to predict that the kind of drought in the United States last summer, and the kind of unusual wetness in some other parts of the world, would, over time, occur a lot more frequently than in the historical record?

Dr. SCHNEIDER. Yes. What it would suggest is that the frequency would increase, I agree. We can never take any one year as a guide. Actually, I have a video if we have time, which I could show on that question later.

But the key from us is that we are not arguing that we have the capacity now to predict how one year is different from the next. What we can do, and I like to use the metaphor of dice, is we can argue that the climate is like dice, but not dice with 12 faces, but with hundreds. And there are wets and dries and so forth, and that nature will continue to roll them, and we will have some unusual years of all kinds.

And what we are doing is erasing some of the cold faces and replacing them with warm. When it is warm, that enhances evaporation stress and that leverages the system toward, apparently, having a higher frequency of dry.

The problem is, where the models are most equivocal, is over whether it gets wetter or drier. But it has to get wetter just to keep up with the extra evaporation. So if you are a complete gambler, you are flipping a coin on whether it is wetter or drier. And you are increasing the temperature, so I would gamble that drier is more likely in the interior of continents, although I do not think that that would necessarily follow in the tropics, because, in fact, I suspect we might even have more rain there.

Okay. Let me conclude, then, by saying, what do we do with all these uncertainties? In order to forecast the future, we have to know what kind of technology we will have. Will we use coal or oil or gas, or will we use nuclear or solar or bio, or some other kind of technology? And they make a substantial difference in how much greenhouse gases there will be, what will happen with the fluorocarbon treaty, and so forth.

The second thing that we have to do then is ask how that is disposed of in the system. And it is simply not possible to have an absolutely certain scenario. So that we do what we believe is the most responsible thing: we tend to scope out as best we can sketch it, high, medium and low rates of change.

And this slide, prepared from an international assessment, shows three such examples. What we are looking at is a change in temperature in the vertical axis and time from 1860 through to 2100, projected.

And the low scenario shows about a half degree celsius warming by 2100, you know about one Fahrenheit additional warming, as the lowest scenario.

There is also a fast change scenario up here, which shows about five degrees warming some time in the middle of the next century. And I have no hesitation to call that one catastrophic, because five degrees Celsius change is about the magnitude of difference between the end of the last ice age and the present, as we will hear in a moment, and it took 5,000 to 10,000 years for that to occur. So we would be looking at rates of change 100 times faster than nature's rates if that scenario occurred.

And then, of course, the middle scenario on that graph shows a warming of several degrees Celsius into the middle of the next century.

That, alone, is unprecedented, because we do not have any evidence that we have been more than a degree or two warmer, literally, during the era of human civilization, or, in fact, much more than two degrees warmer over the past million years.

So the primary cause of concern from any climatologist, myself included, is not that we have detailed and specific forecasts of where it is wetter and drier, or that we can answer the question, even, which of these is more probable, since we have to speculate by our intuition as to the probability of these graphs, but simply that we know that heat trapping works, and we know that we are adding gases, and that the theories tell us that something between one and five degrees warming in the middle of the next century is plausible, or by the end of it; and that that is a rate of change which is somewhere between 10 and 50 times faster than natural rates of change.

And it would be sheer arrogance for us to say that we can give the detailed and specific effects on forests and sea level and other such things to this kind of transient event when we are having enough trouble trying to explain how nature did things more slowly, which will follow in the next testimony; and that, while we try to refine our estimates, we are still continuing to perform this experiment on laboratory Earth.

Thank you.

[The statement follows:]

STATEMENT OF STEPHEN H. SCHNEIDER, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

PREDICTING FUTURE CLIMATE:
CAN IT BE DONE RELIABLY?

The Earth's climate changes. It is vastly different now from what it was 100 million years ago, when dinosaurs dominated the planet and tropical plants thrived at high latitudes; it is different from what it was even 18,000 years ago, when ice sheets covered much more of the Northern Hemisphere. In the future it will surely continue to evolve. In part the evolution will be driven by natural causes, such as slow changes in the Earth's orbit over many thousands of years. But future climatic change, unlike that of the past, will probably have another source as well: human activities. We may already be feeling the climatic effects of having polluted the atmosphere with gases such as carbon dioxide.

How can human societies prepare for so uncertain a climatic future? Clearly it would help to be able to predict that future in some detail, but therein lies a problem: the processes that make up a planetary climate are too large and too complex to be reproduced physically in laboratory experiments. Fortunately, they can be simulated mathematically with the help of a computer. In other words, instead of actually building a physical analogue of the land-ocean-atmosphere system, one can devise mathematical expressions for the physical principles that govern the system -- energy conservation, for example, and Newton's laws of motion -- and then allow the computer to calculate how the climate will evolve in accordance with the laws. Mathematical climate models cannot simulate the full complexity of reality. They can, however, reveal the logical consequences of plausible assumptions about the climate. At the very least they are a big step beyond purely speculative "hand waving" (see Schneider 1987, from which much of this testimony is derived).

Mathematical models have been used to simulate the present climate -- to study, for instance, the effects on the atmosphere of volcanic eruptions such as El Chichon. They are also helping to explain the evolution of past climates, including those of the ice ages and the Cretaceous period (the final age of the dinosaurs). The accuracy of paleoclimatic simulations in turn lends confidence to workers who employ the same models to simulate future climates, and who in particular try to gauge the potential impacts of human pollution. In this context climate modeling is emerging as a field of more than academic interest: it is becoming a fundamental tool for assessing public policy.

Basic Elements

Although all climate models consist of mathematical representations of physical processes, the precise composition of a model and its complexity depends on the problem it is designed to address. In particular they depend on how long a period of the past or future is to be simulated. Some of the processes that influence climate are very slow: the waxing and waning of glaciers and forests, for example, or the motions of the earth's crust, or the transfer of heat from the surface of the ocean to its deeper layers. A model designed to forecast next week's weather ignores these variables, treating their present values (the extent of ice coverage, for instance) as external, unchanging "boundary conditions." Such a model simulates only atmospheric change. On the other hand, a model designed to simulate the dozen or so ice ages and interglacial periods of the past million years must include all the above processes and more.

Climate models vary also in their spatial resolution, that is, in the number of dimensions they simulate and the amount of spatial detail they include. An example of an extremely simple model is one that calculates only the average temperature of the earth, independent of time, as an energy balance arising from the earth's average reflectivity and the average "greenhouse" properties of the atmosphere. Such a model is zero-dimensional: it collapses the real temperature distribution on the earth to a single point, a global average. In contrast, three-dimensional climate models reproduce the way temperature varies with latitude, longitude, and altitude. The most sophisticated of them are known as general-circulation models (GCMs). They predict the evolution with time not only of temperature but also of humidity, wind speed and direction, soil moisture, and other variables.

General circulation models are usually more comprehensive than simpler models in terms of the detail they include, but they are also much more expensive to design and run. The optimal level of complexity for a model depends on the problem and on the resources available to address it; more is not necessarily better. Often it makes sense to attack a problem first with a simple model and then employ the results to guide research at higher resolution. Deciding how complicated a model to use for a given task involves a trade between completeness and accuracy versus tractability and economy. This tradeoff often is more a value judgment based on scientific intuition than a judgment based strictly on scientific method.

Grids and Parameters

Even the most complex GCM is sharply limited in the amount of spatial detail it can resolve. No computer is fast enough to calculate climatic variables everywhere on the earth's surface and in the atmosphere in a reasonable length of time. Instead, calculations are executed at widely spaced points that form a three-dimensional grid at and above the surface. The model my colleagues and I at the National Center for Atmospheric Research use is typically run with a grid with nine layers stacked to an altitude of about 30 kilometers. The horizontal spacing between grid points is roughly 4.5 degrees of latitude and 7.5 degrees of longitude.

The wide spacing creates a problem: many important climatic phenomena are smaller than an individual grid box. Clouds are a good example. By reflecting a large fraction of the incident sunlight back to space or efficiently absorbing and emitting thermal infrared radiant energy, they help to determine the temperature on the earth. Predicting changes in cloudiness is therefore an essential part of reliable climate simulation. Yet no global climate model now available or likely to be available in the next few decades has a grid fine enough to resolve individual clouds, which tend to be a few kilometers rather than a few hundred kilometers in size.

The solution to the problem of sub-grid-scale phenomena is to represent them collectively rather than individually. The method for doing so is known as parameterization. It consists, for example, in searching through climatological data for statistical relations between variables that are resolved by the grid and ones that are not. For instance, the average temperature and humidity over a large area (the size of one grid box, say) can be related to the average cloudiness over the same area; to make the equation work one must introduce parameters, or proportionality factors, that are derived empirically from the temperature and humidity data or from a higher resolution process model. Since a GCM can calculate the temperature and humidity in a grid box from physical principles, it can predict through a parameterization the average cloudiness in the grid box even though it cannot predict individual clouds.

To fully simulate the climate the models must take into account the complex feedback mechanisms that influence it. Snow, for example, has a destabilizing, positive-feedback effect on temperature: when a cold snap brings a snowfall, the temperature tends to drop further because snow, being highly reflective, absorbs less solar energy than bare ground. This process has been parameterized fairly well in climate models. Unfortunately other feedback loops are not as well understood. Again clouds are a case in point. They often form over warm, wet areas of the earth's surface, but depending on the circumstances they may have either a stabilizing, negative-feedback effect (cooling the surface by blocking sunlight) or a positive one (warming the surface further by trapping heat). (For example, see Ramanathan et al. 1989.)

Climate Sensitivity

Uncertainty about the nature of important feedback mechanisms is one reason the ultimate goal of climate modeling -- forecasting reliably the future of key variables such as temperature and rainfall patterns -- is not yet realizable. Another source of uncertainty that is external to the models themselves is human behavior. To forecast, for example, what impact carbon dioxide emissions will have on climate one would need to know how much carbon dioxide is going to be emitted.

What the models can do is analyze the sensitivity of the climate to various uncertain or unpredictable variables. In the case of the carbon dioxide problem one could construct a set of plausible economic, technological and population-growth scenarios and employ a model to evaluate the climatic consequences of each scenario. Climatic factors whose correct values are uncertain (such as parameters in the cloud-feedback parameterization) could be varied over a plausible range of values. The results would indicate which of the uncertain factors is most important in making the climate sensitive to a carbon dioxide buildup; one could then focus research on those factors. The results would also give some idea of the range of climatic futures to which societies may be forced to adapt. How to respond to such information, of course, is a political issue.

Perhaps the most perplexing question about climate models is whether they can ever be trusted enough to provide grounds for altering social policies, such as those governing carbon dioxide emissions (e.g., see the overview by Schneider 1989a). How can models so fraught with uncertainties be verified? There are actually several methods. None of them is sufficient on its own, but together they can provide significant (albeit largely circumstantial) evidence of a model's credibility.

The first method is to check the model's ability to simulate today's climate. The seasonal cycle is one good test because the temperature changes involved are large -- several times larger, on the average, than the change from an ice age to an interglacial period. General-circulation models do remarkably well at mapping the seasonal cycle, which strongly suggests they are on the right track (see, for example, Figure 1). The seasonal test is encouraging as a validation of "fast physics" such as cloudiness changes. However, it does not indicate how well a model simulates slow processes, such as changes in deep ocean circulation, that may have important long-term effects.

A second method of verification is to isolate individual physical components of the model, such as its parameterizations, and test them against a high resolution sub-model or real data from the field. For example, one can check whether the model's parameterized cloudiness matches the level of cloudiness appropriate to a particular grid box. Or, one can test a GCM grid cloudiness against an isolated mesoscale model. The problem with the former test is that it cannot guarantee that the complex interactions of many individual model components are properly treated. The GCM may be good at predicting average cloudiness but bad at representing cloud feedback. In that case the simulation of the overall climatic response to, say, increased carbon dioxide is likely to be inaccurate.

A third method for determining overall, long-term simulation skill is the model's ability to reproduce the diverse climates of the ancient earth (e.g., Barron and Hecht 1985; Berger et al. 1984; Schneider 1987) or even of other planets (e.g., Kasting et al. 1988). Paleoclimatic simulations of the Mesozoic Era, glacial/interglacial cycles, or other extreme past climates help in understanding the coevolution of the earth's climate with living things. As verifications of climate models, however, they are also crucial to estimating both climatic and biological future.

Overall validation of climatic models thus depends on constant appraisal and reappraisal of performance in the above categories. Also important are a models' response to such century-long forcings as the 25 percent increase in carbon dioxide and other trace greenhouse gases since the Industrial Revolution. Indeed, most climatic models are sensitive enough to predict warming of at least $1^{o}C$ should have occurred during the past century. The precise "forecast" of the past 100 years also depends upon how the model accounts for such factors as changes in the solar constant or volcanic dust (e.g., see Schneider and Mass 1975; Gilliland and Schneider 1984; or Hansen et al. 1981). Indeed, as recent data shows, the typical prediction of a degree C warming is broadly consistent but somewhat larger than observed. Possible explanations for the discrepancy include (see Schneider 1989a): (i) the state-of-the-art models are too sensitive to increases in trace greenhouse gases by a rough factor of 2; (ii) modelers have not properly accounted for such competitive external forcings as volcanic dust or changes in solar energy output; (iii) modelers have not accounted for other external forcings such as regional tropospheric aerosols from agricultural, biological, and industrial activity; (iv) modelers have not properly accounted for internal processes that could lead to stochastic or chaotic behavior; (v) modelers have not properly accounted for the large heat capacity of the oceans taking up some of the heating of the greenhouse effect and delaying, but not ultimately reducing, warming of the lower atmosphere; (vi) both present model forecasts and observed climatic trends could be consistent since models are typically run for equivalent doubling of carbon dioxide whereas the world has only experienced a quarter of this increase and nonlinear processes have been properly modeled and produced a sensitivity appropriate for doubling but not for 25% increase; and (vii) the incomplete and inhomogeneous network of thermometers has underestimated actual global warming this century.

Despite this list of excuses why observed global temperature trends in the past century and those anticipated by most GCMs disagree somewhat, the two-fold discrepancy is still encouraging. Most climatologists do not yet proclaim the observed temperature records to have been caused beyond doubt by the greenhouse effect. Thus, a greenhouse effect signal cannot yet be said to be unambiguously detected in the record. It is possible that the observed trend and the predicted warming could still be chance occurrences. One cannot easily rule out that other factors, such as solar constant variations or volcanic dust, simply have not been adequately accounted for over the past century -- except during the past decade when adequate instruments have been measuring them. Nevertheless, this empirical test of model predictions against a century of observations certainly is consistent to a rough factor of 2. This test is reinforced by the good simulation by most climatic models of the seasonal cycle, diverse ancient paleoclimates, hot conditions on Venus, cold conditions on Mars (both well simulated), and the present distribution of climates on earth. When taken together, these verifications provide a strong circumstantial case that the modeling of sensitivity of the global surface air temperature to greenhouse gases is probably valid within roughly two-fold. Another decade or two of observations of trends in earth's climate, of course, should produce signal-to-noise ratios sufficiently obvious that almost all scientists will know whether present estimates of climatic sensitivity to increasing trace gases have been predicted well or not.

The Modern Greenhouse

There is no doubt that the concentration of carbon dioxide in the atmosphere has been rising; it is roughly 25 percent higher now than it was a century ago. It is also broadly accepted that when the carbon dioxide concentration rises, the temperature at the Earth's surface must rise too. Carbon dioxide is relatively transparent to visible sunlight, but it is more efficient at absorbing the long-wavelength, infrared radiation emitted by the Earth. Hence it tends to trap heat near the surface. That is the greenhouse effect, and its existence is not questioned. It explains the very hot temperatures on Venus (whose thick atmosphere is mostly carbon dioxide) as well as the frigid conditions on Mars (whose carbon dioxide atmosphere is very thin).

What is not a consensus is the precise amount of warming and the regional pattern of climatic change that can be expected of the Earth from a specific increase in the atmospheric concentration of carbon dioxide and other greenhouse gases. (The cumulative effect of chlorofluorocarbons, nitrogen oxides, ozone and other trace gases could be comparable to that of carbon dioxide over the next century -- Ramanathan, Cicerone, Singh, and Kiehl 1985.)

It is this regional pattern of changes in temperature, precipitation and soil moisture that will determine what impact the greenhouse effect will have on ecosystems, agriculture and water supplies.

A number of workers have attempted to model the possible climatic impacts of carbon dioxide. Most of them have followed the same approach: they give the model an initial jolt of carbon dioxide (usually doubling the atmospheric concentration), allow it to run until it reaches a new thermal equilibrium and then compare the new climate to the control climate. In one of the most widely cited results, Syukuro Manabe and Richard T. Wetherald (1986) of the Geophysical Fluid Dynamics Laboratory at Princeton University have found that both a doubling and a quadrupling of atmospheric carbon dioxide would produce a summer "dry zone" in the North American grain belt, but that soil moisture in the monsoon belts would increase. Such a dry zone would substantially reduce corn yields in the Corn Belt or lake levels in the Great Lakes (e.g., Smith and Tirpak 1988). The G.F.D.L. model reached its new equilibrium after several decades of simulated time.

In reality, however, the approach to equilibrium would probably be much slower. This version of the G.F.D.L. model omitted both the horizontal transport of heat in the ocean and the vertical transport of heat from the well-mixed surface layer to the ocean depths. Both processes would slow the approach to thermal equilibrium; the real transition would probably take more than a century. Heat transport in the oceans would also affect the temperature response to a realistic, gradual increase in greenhouse gases, as opposed to the one-time injection.

Schneider and Thompson (1981) developed simple one-dimensional models that demonstrated the importance of the transient phase of warming. Regions at different latitudes approach equilibrium at different rates, essentially because they include different amounts of land; land warms up faster than the oceans. Also, oceans have different vertical mixing rates at different locations. Hence during the transient phase, the warming and other climatic effects induced by the enhanced greenhouse effect could well display world-wide patterns significantly different from the ones inferred on the basis of equilibrium GCM simulations. Furthermore, the social impact of climatic changes would probably be greatest before equilibrium has been reached and before human beings have had a chance to adapt to their new environment.

To represent the transient phase adequately one would need to couple a three-dimensional model of the atmosphere with a three-dimensional model of the ocean that includes the effects of horizontal and vertical heat transport. A handful of coupled models have been run, but none for long enough to simulate the next century (e.g., Bryan, Manabe, and Spelman 1988; Washington and Meehl 1989). The coupled models are still too uneconomical for that task, and they are also not yet trustworthy enough. Once they have been improved, one will be able to state with more confidence how the climatic impacts of rising levels of greenhouse gases might be distributed in space and time. Until then one can only cite circumstantial evidence that the impacts are likely to be significant: e.g., the present GCMs simulate past climates or the present seasonal cycle well, or the Earth is already about 0.5 degrees C warmer than it was a century ago, or the 1980s are the warmest decade on record.

Society is thus faced with a classic example of the need to make decisions with imperfect information. Some projected climatic impacts appear severe; but perhaps these could be mitigated if we know what to expect and if we choose to respond. At the same time, there is a risk of investing resources to prevent an impact that may not appear, or that may appear where least expected -- as the Antarctic "ozone hole" exemplifies. The need to know details about the timing and distribution of future climate changes has been stated in many scientific and political forums, and detailed climate impact studies have been commissioned.

In an effort to shed some light on these questions, Schneider, Gleick, and Mearns (1989) offered a set of "forecasts" on changes in some important meteorological variables, over a range of temporal, spatial, and statistical scales. I believe that carefully qualified, explicit scenarios of plausible future climatic changes are preferable to impact speculations based on implicit or casually-formulated forecasts. Therefore I include Table 1 to provide impact assessment specialists with ranges of climate changes that reflect our interpretation of state-of-the-art modeling results. These projections are based on our analysis of available results and provide what I believe are plausible estimates about the direction or magnitude of some important anthropogenic climatic changes over the next 50 years or so--a typical estimate for an equivalent doubling of carbon dioxide--together with a simple high, medium, or low level of confidence for each variable. (By "equivalent doubling", it is meant that carbon dioxide together with other trace greenhouse gases have a radiative effect equivalent to doubling the pre-industrial value of carbon dioxide from about 280 ppm to 560 ppm.) As another measure of the nature of the uncertainties, a rough estimate is included of the time that may be necessary to achieve a widespread scientific consensus (not unanimity which is unachievable) on the direction and magnitude of the change. In some cases--such as the magnitude and direction of changes in sea level and global annual-average temperature and precipitation--such a consensus is building rapidly. In other cases, such as the changing extent of cloud cover, time-evolving patterns of regional precipitation, or the daily, monthly, or interannual variance of many climatic variables, the large uncertainties surrounding present projections will only be reduced with considerably more research -- probably taking many decades at present levels of effort.

Let us consider, for example, the first row on Table 1: temperature change. The global average change of +2 to +5 degrees C is typical of that in most national and international assessments for an equivalent doubling of greenhouse gases, neglecting transient delays. The neglect of transients means that the range given is based on the assumption that trace gases have been increased over a long enough period for the climate to come into equilibrium with the increased concentration of greenhouse gases. In reality, the large heat capacity of the oceans will delay realization of most of the equilibrium warming by perhaps many decades. This implies, I said earlier, that at any specific time when we reach an equivalent CO_2 doubling (by say 2030), the actual global temperature increase may be considerably less than the +2 to +5 degrees C listed in Table 1. However, this "unrealized warming" (e.g. see Hansen et al. 1985) will eventually be experienced when the climate-system thermal response catches up to the greenhouse-gas forcing.

Forecasts of regional- or watershed-scale changes in temperature, evaporation, or precipitation are most germane to impact assessment. But, as Table 1 suggests, such regional forecasts are much more uncertain than global equilibrium projections. Regional temperature ranges given in Table 1 are much larger than global changes, and even allow for some regions of negative change. For example, higher northern latitude surface temperature increases are up to several times larger than the global average response, at least in equilibrium. Because of the importance of regional or local impact information, techniques need to be developed to evaluate smaller-scale effects of large-scale climatic changes. (For example, Gleick 1987, employed a regional hydrology model driven by large-scale climate change scenarios from various GCM inputs.)

Even more uncertain than regional details, but perhaps most important, are estimates for measures of climatic variability such as the frequency and magnitude of severe storms, enhanced heat waves, or reduced frost probabilities (e.g., Mearns et al. 1984 or Parry and Carter 1985). For example, some modeling evidence suggests that hurricane intensities will increase with climatic changes (Emanuel 1987). Such issues are just now beginning to be considered and evaluated from equilibrium climate-model results, and will, of course, have to be studied again for realistic transient cases to be of maximum value to impact assessors.

Another uncertainty raised by the transient nature of the actual trace gas forcing is the emission and removal rates of CO_2, CH_4, and other greenhouse gases. Figure 2 shows three plausible scenarios based on high, medium, and low emission rates. These uncertainties have been added to those associated with estimates of climate sensitivity and the delay associated with oceanic heat capacity. It is impossible to objectively assign probabilities to each of these three curves, but I can offer my intuitive estimates: the high and low scenarios are not too likely (say, a 10% chance each) and everything in between much more likely. In any case, since the earth has apparently not experienced global average temperatures more than 1-2 degrees C warmer than at present over the past glacial cycle (150,000 years), all but the slowest scenario in Fig. 2 represents a rapid, large climatic change to which the environment and society will have to adapt.

The principal technical advance needed to help build consensus on the reliability of time-evolving regional forecasts of hydrological variables is the development, testing, and verification of coupled atmosphere/ocean/land/biota models, driven by realistic transient trace gas forcing scenarios. Fortunately, there has been recent progress in the development of such models (e.g., Washington and Meehl 1989; Bryan et al. 1988), although it is suggested in Table 1 that it will be at least a decade before high confidence in the reliability of regional forecasts will achieve a large scientific consensus. (Personally, I think several decades is a more realistic estimate.) A greatly enhanced and better coordinated modeling and observational initiative will be needed if this several-decade time frame I estimate before credible regional scenarios can be produced is to be accelerated.

Some scientists may object in principle to the approach taken in Table 1, arguing that since the confidence levels cited are intuitive, they may be incorrect, or even that some eventual change could be in the opposite direction of that listed. Indeed, predictions about something as complex as the global climate system response to forcings controlled by human behavior will always be somewhat uncertain. Nevertheless, many policy makers are likely to have a contrasting reaction--the information in Table 1, even if certain, may still not contain enough detail to justify major policy decisions. Policy analysts typically want regional details even finer than those typically available -- e.g., those that have been provided on maps given in the survey article by Schlesinger and Mitchell (1987), a few of which are reproduced here as Figs. 3, 4, 5, and 6. This schism -- between some scientists' reticence to make any forecasts and some policy analysts' insistence on high levels of regional detail -- cannot be resolved simply by having the latter fashion their own speculative or implicit scenarios for impact assessment. Rather, I believe, it is better to have knowledgeable scientists putting forth a range of plausible "forecasts" based on the best available information.

As the state-of-the-art evolves, such scenarios will need to be regularly revised and improved, and the implications for environmental and societal impacts reassessed. Through this iterative process climate scientists hope that clearer understanding of potential climatic impacts will develop. Of course, while scientists study and debate, the world becomes committed to a growing dose of greenhouse gases and their impacts. The rates at which anthropogenic climate change could be evolving (as in Fig. 2) are extremely rapid when compared to most paleoclimatic trends (see Schneider 1989b). It is questionable whether natural ecosystems and human activities can adapt easily to such plausible rates of change, suggesting some urgency for accelerating the rate at which the scientific community is likely to resolve uncertainties in climatic scenarios and impact assessments.

TABLE 1

PHENOMENA	PROJECTION OF PROBABLE GLOBAL ANNUAL AVERAGE CHANGE (1)	DISTRIBUTION OF CHANGE: REGIONAL AVERAGE	CHANGE IN SEASONALITY	INTERANNUAL* VARIABILITY	SIGNIFICANT TRANSIENTS	CONFIDENCE OF PROJECTION: GLOBAL AVERAGE	REGIONAL AVERAGE	ESTIMATED TIME FOR RESEARCH THAT LEADS TO CONCENSUS (YEARS)
TEMPERATURE	+2 TO +5 C	-3 TO +10 C	YES	DOWN?	YES	HIGH	MEDIUM	0 TO 5
SEA LEVEL	+10 TO +100 cm	(2)	NO	???	UNLIKELY	HIGH	MEDIUM	5 TO 20
PRECIPITATION	+7 TO +15%	-20 TO +20%	YES	UP?	YES	HIGH	LOW	10 TO 50
DIRECT SOLAR RADIATION	-10 TO +10%	-30 TO +30%	YES	???	POSSIBLE	LOW	LOW	10 TO 50
EVAPOTRANSPIRATION	+5 TO +10%	-10 TO +10%	YES	???	POSSIBLE	HIGH	LOW	10 TO 50
SOIL MOISTURE	???	-50 TO +50%	YES	???	YES	???	MEDIUM	10 TO 50
RUNOFF	INCREASE	-50 TO +50%	YES	???	YES	MEDIUM	LOW	10 TO 50
SEVERE STORMS	???	???	???	???	YES	???	???	10 TO 50

NOTES

(1) For an "equivalent doubling" of atmospheric CO_2 from the preindustrial level. These are equilibrium values, neglecting transient delays and adjustments.

??? No basis for quantitative or qualitative forecast.

(2) Increases in sea level at approximately the global rate except where local geological activity prevails.

* Inferences based on preliminary results for the U.S. of D. Rind (GISS, personal communication).

FIGURE CAPTIONS

1. A three-dimensional climate model has been used to compute the winter to summer temperature extremes all over the globe. The model's performance can be verified against the observed data shown below. This verification exercise shows that the model quite impressively reproduces many of the features of the seasonal cycle. These seasonal temperature differences are mostly larger than those occurring between ice ages and interglacials or for any plausible near-future carbon dioxide change. Although this approach cannot validate models for processes occurring on medium to long time scales (greater than 1 year), they are very encouraging for validating to a rough factor of 2 such "fast physics" parameterizations like clouds. [Source: S. Manabe and R. J. Stouffer, *J. Geophys. Res. 85*: 5529 (1980).]

2. Three scenarios for global temperature change to 2100 derived from combining uncertainties in future trace greenhouse gas projections with those of modeling the climatic response to those projections. Sustained global temperature changes beyond 2°C (3.6°F) would be unprecedented during the era of human civilization. The middle to upper range represents climatic change at a 10 to 100 times faster pace than long-term natural average rates of change. [Source: J. Jager, *Developing Policies for Responding to Climatic Change, A Summary of the Discussions and Recommendations of the Workshops Held in Villach 28 September to 2 October 1987* (WCIP-1, WMO/TD-No. 225, April 1988).]

3. Geographical distribution of the surface air temperature change (in degrees Celsius), (2 x CO_2) - (1 x CO_2), for DJF simulated with (top) the GFDL GCM, (middle) the GISS GCM, and (bottom) the NCAR GCM. Stippling indicates temperature increases larger than 4°C. For reference to particular versions of the GCMs used, see M. E. Schlesinger and J.F.B. Mitchell, *Rev. Geophys. 25*:760-798 (May 1987).

4. Same as Figure 3, except for JJA.

5. Geographical distribution of the precipitation rate change (in millimeters per day), (2 x CO_2) - (1 x CO_2), for DJF simulated with (top) the GFDL GCM, (middle) the GISS GCM, and (bottom) the NCAR GCM. Stippling indicates a decrease in precipitation rate. For details of which specific GCM versions were chosen, see M. E. Schlesinger and J.F.B. Mitchell, *Rev. Geophys. 25*:760-798 (May 1987).

6. Same as Figure 5, except for JJA.

FIGURE 1

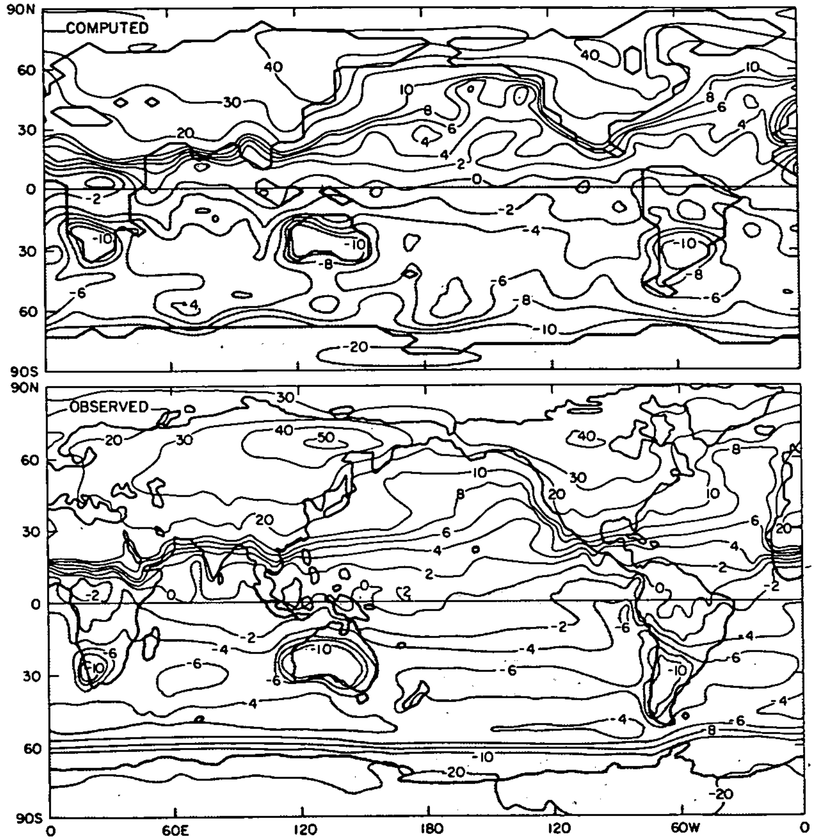


FIGURE 2

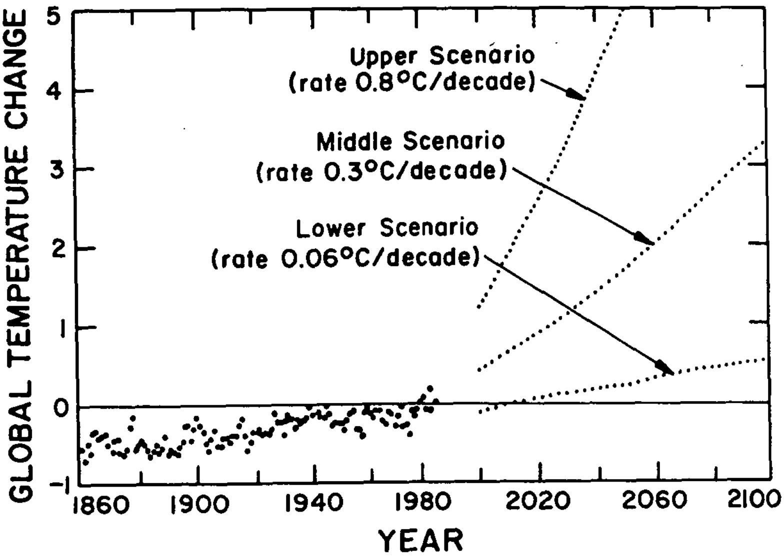

GLOBAL TEMPERATURE CHANGE
5
4
3
2
1
0
-1
Upper Scenario
(rate 0.8°C/decade)
Middle Scenario
(rate 0.3°C/decade)
Lower Scenario
(rate 0.06°C/decade)
1860
1900
1940
1980
2020
2060
2100
YEAR

FIGURE 3

TEMPERATURE DIFFERENCES FOR DJF

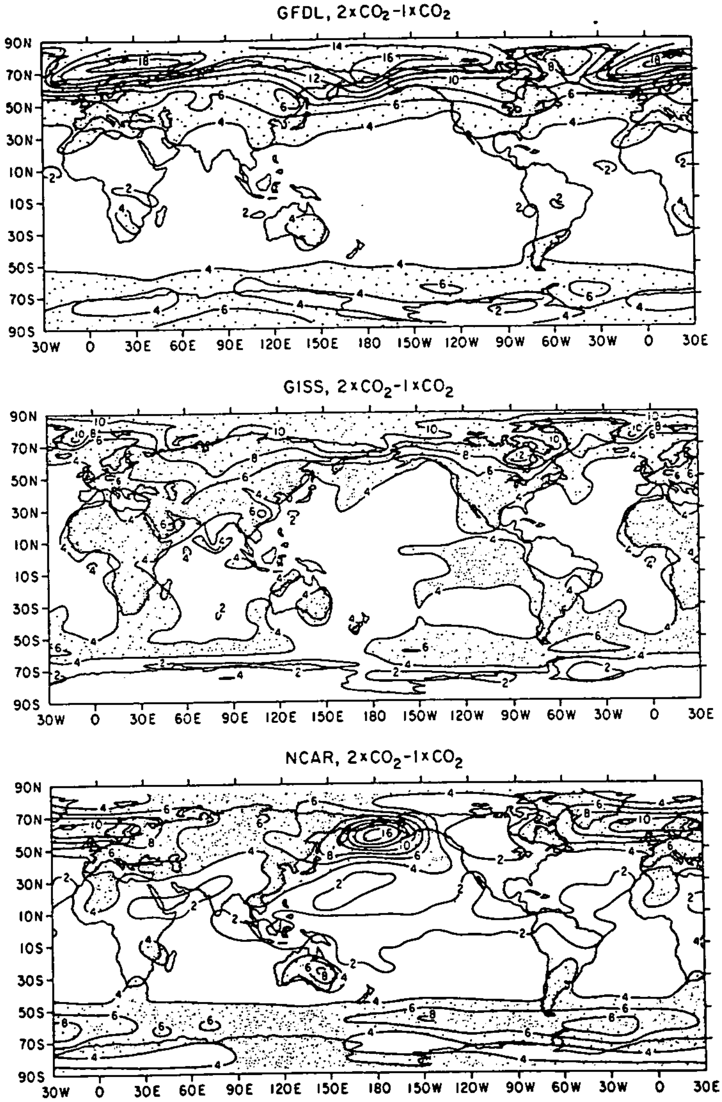


FIGURE 4

TEMPERATURE DIFFERENCES FOR JJA

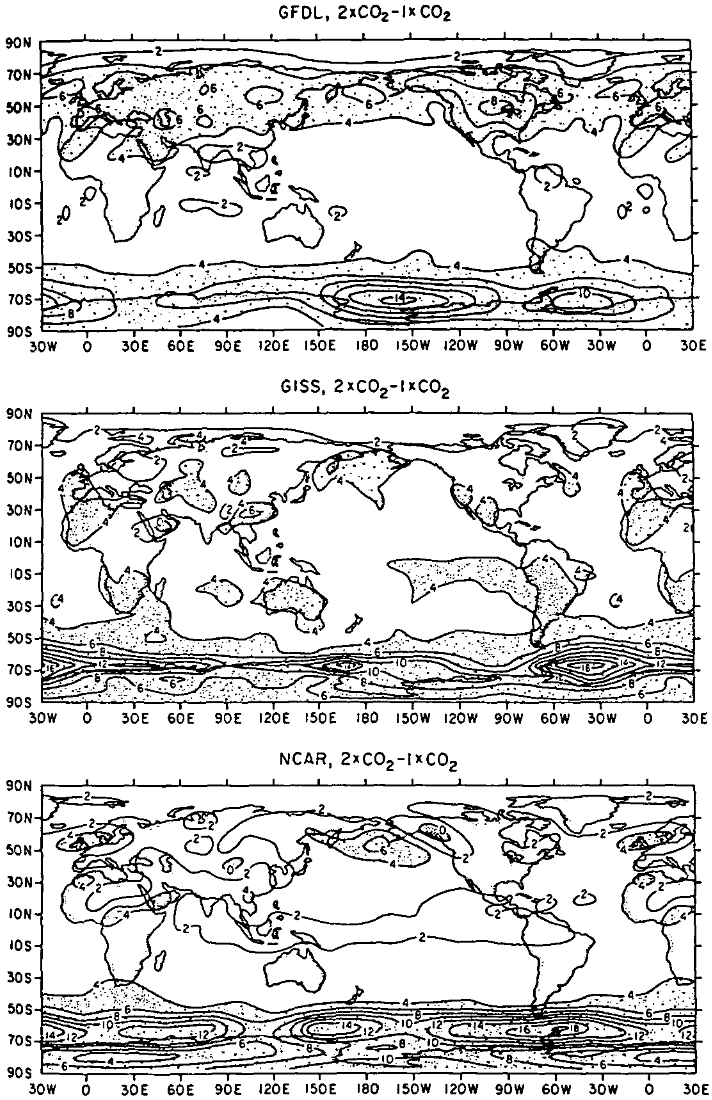


FIGURE 5

PRECIPITATION DIFFERENCES FOR DJF

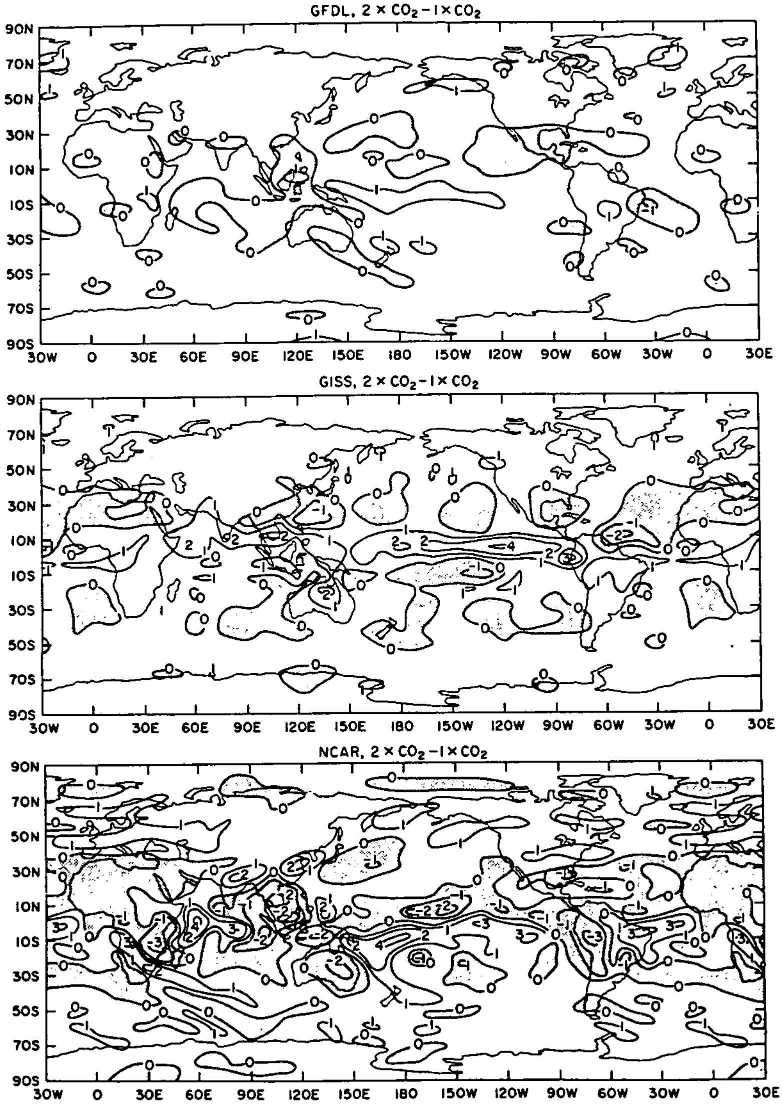
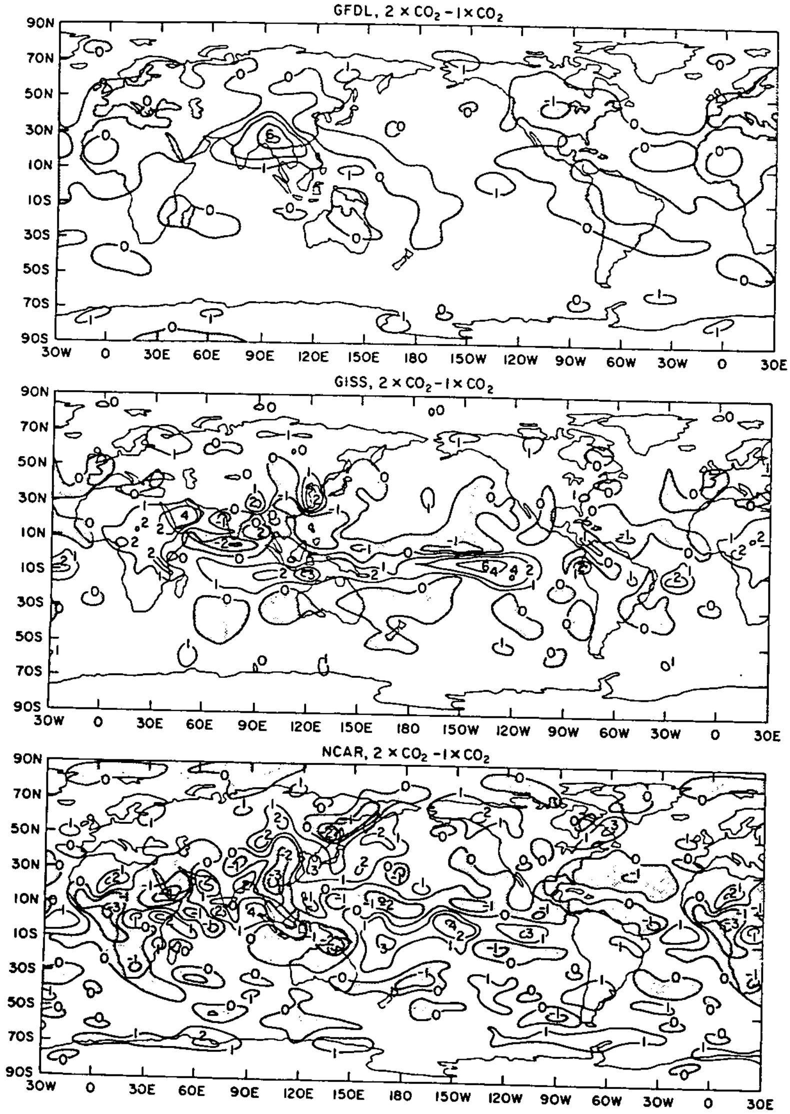


FIGURE 6

PRECIPITATION DIFFERENCES FOR JJA



Senator GORE. Thank you very much, Dr. Schneider.

Our second witness on this panel is Dr. Dallas Peck, Director of the U.S. Geological Survey.

Thanks for joining us, Dr. Peck. Please, proceed.

Dr. PECK. Thank you, Senator.

If I may, I will go up to the boards that I brought to explain my presentation.

I am talking today as a geologist. I am talking about the geologic record, because preserved in the geologic record is the record of the climate change over the last several hundreds of millions of years, and in some detail over the last million years or so.

The record is preserved in fossils and sediments on land and in marine sediments, and also in air bubbles in glacier cores.

This shows the variability of climate over three different time scales. This is important in a number of ways. It tells us the rate of change of climate, what the climate has been like in the past, how vegetation changes with changing climate. It also presents an opportunity for testing or hindcasting of predictive models generated by our colleagues, maybe several of who will be making presentations today.

Over the last 140 million years, shown in the top graph here, you can see the bottom temperatures in low-latitude waters decrease markedly from the early Cretaceous, 140 million years ago until now, and particularly over the last 20 or 30 million years. This is probably reflecting the growth of ice in Antarctica and the more abundant bottom currents from both the Arctic and the Antarctic. Surface temperatures probably remained nearly constant or decreased at a much lesser rate.

We do not really understand why this changed, but it may well be related to the shifting continents, plate tectonics, and changes in ocean currents.

Now, over the last two million years, this is 140 million years, so, here is about two million years, and we are now going to expand that into this record here.

This goes back to about the beginning of the ice ages. This is the average temperature right now in the world, about 15 degrees centigrade. As you can see, there is quite a lot of variation, but mostly the temperatures were colder than today—during the height of the ice ages, about 5 degrees colder than today down here.

Senator BRYAN. Is that graph depicting ocean temperatures or atmospheric temperatures, the second one, the one that you are pointing to now?

Dr. PECK. This is reflecting surface water temperatures.

Senator GORE. Your line there says global mean annual air temperature.

Dr. PECK. That is right.

Senator GORE. But the surface water——

Dr. PECK. The data are based on oxygen isotopes in plankton, minute animals in the ocean.

Senator GORE. All right.

Dr. PECK. With so many experts in the room, I will not compare what annual air temperature is with average surface temperature, because they know better than I do.

But as you can see, the surface temperatures did not exceed the current temperature by more than a couple of degrees. So mostly over the last two million years, during the generation of modern man, temperatures were a lot colder.

Okay. The bottom graph shows, in a somewhat simplified and generalized form, temperatures over the last 11,000 years, which means since the end of the last ice age.

As you can see, the temperatures have fluctuated considerably over the last 11,000 years, since the last ice age. And, in part, they have been several degrees warmer—again, based on reconstruction of past vegetation, based on pollen and sediments and that sort of thing, and also colder. In many ways, the current increase in temperature of the last 100 years or so could be viewed as the temperature increases coming out of the little ice age.

Now, these data are from fossils and marine sediments. But we also have a fair amount of data on past air temperatures and CO_2 abundance from ice cores. Just to show you what that is, this is an example of an ice core from a glacier in Chile. This shows an exposure of glacial ice with annual layers in the ice. By taking cores through that, we can reconstruct the oxygen isotope abundance, and hence, temperatures, and also carbon dioxide abundance and methane abundance, over the last 180,000 years.

Senator GORE. Sort of like tree rings?

Dr. PECK. That is right. This is very much an international activity. The best core was taken by the Soviets and studied mostly by the Swiss and the French and our people, too. So it is a global problem and the solution and understanding is a global phenomena.

Okay. Then we can kind of go back in time to the last ice age, and this poster here shows the ice 18,000 years ago, and the vegetation in broad categories.

This was work done by two scientists, Delcort and Delcort at the East Tennessee University as a matter of fact.

Senator GORE. Excellent work.

Dr. PECK. Again, it is an activity that we in the Geological Survey and scientists all around the world are involved in. We are starting to work with the Canadians and the Soviets on this.

As you can see, 18,000 years ago, the ice extended past New York City, into Pennsylvania, way south of Chicago, and just for the fun of it, here are several satellite images of Antarctica. This one is sort of what Boston looked like, because this is the ice sheet, and it is sort of breaking up offshore. This is what Chicago probably looked like, sort of unbearable you might say, Senator, in its whiteness.

Senator GORE. You cannot even see the Sears Tower poking up out of that.

Dr. PECK. Well, that is right. It was probably a mile thick or thereabouts. Farther north in Canada, it was probably two and a half miles thick.

Okay. Down in your neck of the woods, Senator, in Tennessee, you can see this boreal forest—extending across here—is like the forest of spruce and fir that you get in northern Maine and a good part of Canada. That extended across the northern part of South Carolina and most of Tennessee was in it.

Up along the Mississippi River, again, reconstructing from pollen in sediments, you have a spruce-larch forest, a forest that you get much farther north today.

The forests 18,000 years ago were rather different than today, and it is not just a matter of shifting the forest south, because trees and plants migrate at different rates. So in response to a change in temperature, different species will migrate differently.

So it was a different mixture of trees 18,000 years ago.

In contrast, this just shows what the forests look like today, a rather dramatic shift, and that reflects five degrees difference in temperature.

Finally, I will show, for our friends from the West Coast, what it looked like during the Pleistocene, 10,000 to 25,000 years ago in the Great Basin. Because of the big mass of continental ice occupying most of Canada down into the northern part of the United States, the jet streams were going farther south. I am on dangerous ground because I am a geologist, not a climatologist.

But this seems to be a good example of testing the climate models using past climates. It was a good deal wetter—there was more water around the Great Basin 10,000 to 25,000 years ago. Those lake deposits are very well preserved.

That concludes my testimony. The main point is that we can see the variation in climate in the past, and we can use that variation to test models.

[The statement follows:]

STATEMENT OF DALLAS L. PECK, DIRECTOR
U.S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR
BEFORE THE
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND SPACE
UNITED STATES SENATE
MAY 8, 1989

The geologic record contains a rich storehouse of evidence about past environmental conditions on planet Earth spanning hundreds of millions of years. Geologists interpret the evidence from the geologic record to reconstruct the history of climate and environments on all time scales. Many innovative techniques have been developed to extract the history of climate from the geologic evidence preserved in the form of fossil assemblages, sediment types, sediment chemistry, and features such as ancient shorelines and glacial deposits. Ice cores from glaciers preserve records of past temperatures, precipitation, atmospheric dust content (including volcanic ash), and past changes in composition of the atmosphere. Sediment cores from lakes and the oceans contain long histories of changing climate and environmental conditions at a single location. By examining evidence of the same age from many localities, from both terrestrial and marine sites, it is possible to recreate "snapshots" of global conditions at times in the past when climate was different than that of the present day. Examining the record of past climates of the Earth can provide insights into some of the causes of climate change, the natural variability of climate on all time scales (decades to millions of years), the rates at which past climate changes occurred, and the consequences of climate change. Such knowledge can help improve our ability to anticipate future climate changes and their likely effects on the environment. Information about past global climatic and environmental conditions can also be used to test and improve General Circulation Models. Such models are currently being used to estimate the probable climatic consequences of changes in atmospheric composition caused by human activities, i.e., enhancement of the "greenhouse effect" through burning of fossil fuels, forest clearance, and other activities.

EXHIBIT BOARD #1: NATURAL VARIABILITY OF GLOBAL CLIMATE OCCURS ON ALL TIME SCALES

The geologic record shows that Earth's climate has varied substantially in the past, and evidence of past variability of climate can be seen on all time scales. While the causes of climate change are not well understood, we do know that different major influences on global climate operate on various time scales.

A. THE PAST 140 MILLION YEARS:

- o Reconstruction of the temperature of deep ocean waters during the past 140 million years (based on oxygen isotope variations preserved in marine fossils) shows that the overall temperature trend over the past 90 million years has been towards colder conditions.

- Superimposed upon the long-term trend towards cooler conditions are significant climatic oscillations on time scales of millions of years, the causes of which are poorly understood.
- The global cooling trend implied by the deep water ocean temperature reconstructions for the past ca. 90 million years cannot be adequately explained by any single mechanism. It is likely, however, that this cooling trend resulted from the effects of changes in the configurations of continents and ocean basins over time. On time scales of tens of millions of years, geologic processes such as plate tectonics change positions of continents and seas, which in turn can influence global climate. For example, break-up of the supercontinent Pangea during the late Cretaceous (100-66 million years ago) and subsequent movement of land masses towards high latitudes placed more land in polar regions, e.g., Antarctica, thus creating conditions that favored the accumulation of ice and snow. Shifting positions of continents also altered ocean basin configuration, which altered patterns of ocean heat transport. The opening of the Atlantic Ocean, for example, allowed development of more efficient oceanic

circulation between high and low latitudes. This has resulted in transport of cold waters from polar regions into the deep ocean basins at low latitudes. Warm surface waters are carried by currents such as the Gulf Stream from low latitudes to temperate and high latitudes. This results in milder climates in some adjacent lands (e.g., western Europe) than might be expected at those latitudes.

B. THE PAST 2 MILLION YEARS:

Climate changes that occurred over time intervals of tens of thousands to hundreds of thousands of years have been reconstructed for the past two million years from evidence in sediment cores from the oceans. Variations in oxygen isotopes preserved in marine fossils over thousands of years are plotted as a graph and interpreted as a temperature record in Exhibit 1-B. Current evidence suggests that much of the climatic variability observed during the past two million years, on time scales of tens of thousands to about one hundred thousand years can be explained by celestial mechanics. Systematic variations in the position of Earth in its orbit in relationship to the sun, and the changing shape of the orbit over time alters the amount and global distribution of solar energy that strikes the Earth. These orbital factors appear to have had a significant influence on the Earth's climate.

- Most of the past 2 million years of Earth history has been characterized by climates cooler or significantly colder than that of the present day.

- The present global mean annual temperature is about 15 degrees Celsius (59 degrees Fahrenheit). Only a few tens of thousands of years out of the last 2 million years have been characterized by climates as warm as that of the past 10,000 years (the Holocene epoch).
- During the coldest intervals of the last 2 million years, global mean annual temperature dropped about 5 degrees Celsius (9 degrees F).
- During the warmest intervals of the last 2 million years, global temperatures are not likely to have been any warmer than about 2 degrees C (3.6 degrees F) above present day mean annual temperature (15 degrees C).
- A rapid warming for the next century of 2 to 5 degrees C (3.6 to 9 degrees F), which is the general consensus of General Circulation Models (GCM's) when they are run using fossil fuel scenarios to estimate the transient response of the climate system, would be a very unusual event in recent Earth history (the past 2 million years or more). If such a rapid warming were to occur, it would be difficult to fully anticipate its consequences. Unfortunately, there is a high degree of uncertainty about the likely rate of warming. Most GCM's have been run to estimate the equilibrium warming which would eventually result from an instantaneous doubling of CO2 rather than the slow

growth in CO_2 levels in the atmosphere. The National Academy of Sciences Carbon Dioxide Assessment Committeee has pointed out that:

> "the capabilities of even the most advanced current models remain severely limited; for example the three-dimensional GCM's are generally deficient in the treatment of ocean heat transport and dynamics and feedback between the ocean and the atmosphere."

Since the transient response of the climate over time depends on the heat and CO_2 interactions of the ocean and atmosphere which comprise one of the major areas of deficiency of the models, there is great uncertainty about these estimates of rates of warming.

C. THE PAST 11,000 YEARS:

A simplified temperature curve showing approximate variation in global mean annual temperature spanning the past 11,000 years shows that significant climate changes have occurred on time scales of centuries during that interval. The warming interval 10,500 to about 9,500 years ago was the transition from glacial to "interglacial" climates.

- During the past 10,000 years there have been several intervals when global temperatures where as much as 1.5 to 2 degrees C (2.7 to 3.6 degrees F) warmer than today. None of these previous warming events, which appear to have lasted about 1000 to 1500 years, were caused by human influences on the environment.

- Several intervals of cooler-than-present climate have occurred during the past 10,000 years. The most recent event, called the "Little Ice Age," ended only about 1850 A.D. At least some of the apparent global warming during the last 140 years may be a natural variation, or "recovery" from the Little Ice Age. This complicates the interpretation of possible causal relationships between the apparent global temperature increases of the past century and the observed increases in carbon dioxide content of the atmosphere during that time.
- The causes of climate oscillations on time scales of decades to millenia during the past 10,000 years are not well understood. Additional research is needed to improve our knowledge of the causes of natural variability of climate on these shorter time scales.

EXHIBIT BOARD #2: THE EASTERN U.S. 18,000 YEARS AGO: VEGETATION, GLACIERS, SEA LEVEL, AND SEA-SURFACE TEMPERATURES:

Many types of geologic data can be used to produce reconstructions of past environmental conditions of a region, a continent, or the entire world. This map was based on the distribution of glacial deposits, pollen evidence from lakes, and fossil and isotopic evidence from marine sediment cores. It provides a snapshot of the Eastern United States under a very different climatic regime 18,000 years ago (full-glacial climate, ca. 5 degrees C colder global mean annual temperature than today). Sites of present-day northern cities such as Chicago, Detroit, New York, and Boston were buried under thousands of feet of glacier ice at that time; such environments were comparable to the present-day ice sheets of Greenland and Antarctica. South of the edge of the ice sheet 18,000 years ago, the Eastern United States was quite different than it is today: substantially cooler and drier than today, with dramatically different vegetation cover in most areas, and with a very different coastline. Sea level was more than 300 feet lower than it is today because so much water was being stored on land as glacier ice.

Tundra vegetation grew as far south as southern Ohio, adjacent to the glacier edge, and conifer forests (boreal forest) of pine, spruce, and fir grew as far south as South Carolina, Tennessee and Missouri. Today such forests grow in north of the Great Lakes in Canada. The present site of Memphis, Tennessee was apparently within a narrow zone of broadleaf deciduous forest (mesophytic forest) bordering the Mississippi River, but surrounded by vast tracts of conifer forests.

The numerous species of broadleaf deciduous trees such as oak, hickory, and elms, basswood and many others that are common elements in the diverse forests of Eastern United States today were largely restricted to a zone paralleling the Gulf Coast 18,000 years ago. Geologic evidence suggests that even in the southeastern U.S. the forests during glacial times were composed of odd mixtures of species that in many cases are not found growing together today.

Sites of coastal cities such as Charleston, South Carolina, were more than 100 miles from the ocean 18,000 years ago. The coastal areas were cooler and drier than today.

Information about global conditions during a past interval of glacial climate tells us what the effects of a future global cooling may have. Our immediate concern is the prospect of a global warming during the next century, however. In order to provide insights into the probable consequences of a significant global warming during the next century, the USGS is currently reconstructing global climate and environmental conditions during an interval of substantially warmer climate 2.6 to 3.0 million years ago, during the Pliocene. This research is based on a wide spectrum of geologic evidence from marine and terrestrial sites.

EXHIBIT BOARD #3: THE EASTERN U.S., PRESENT DAY CONDITIONS OF VEGETATION, SEA LEVEL, AND SEA-SURFACE TEMPERATURES:

This map shows the contrast between full-glacial environments 18,000 years ago (exhibit board #3) and present-day environments in the Eastern U.S. The geologic record shows that the transition from full-glacial climate to warm "interglacial" climate occurred over several thousands of years. The vegetation patterns that exist today developed over a period of thousands of years following the end of glacial conditions about 10,000 years ago. Geologic evidence indicates that individual species respond in different ways to climate change, and individual species migrate at different rates. This suggests that any major changes in climate in the future will result in ecosystem changes that may be difficult to anticipate, particularly if the rate of onset of climate change is very rapid.

EXHIBIT BOARD #4: GREAT BASIN LAKES DURING THE PLEISTOCENE EPOCH:

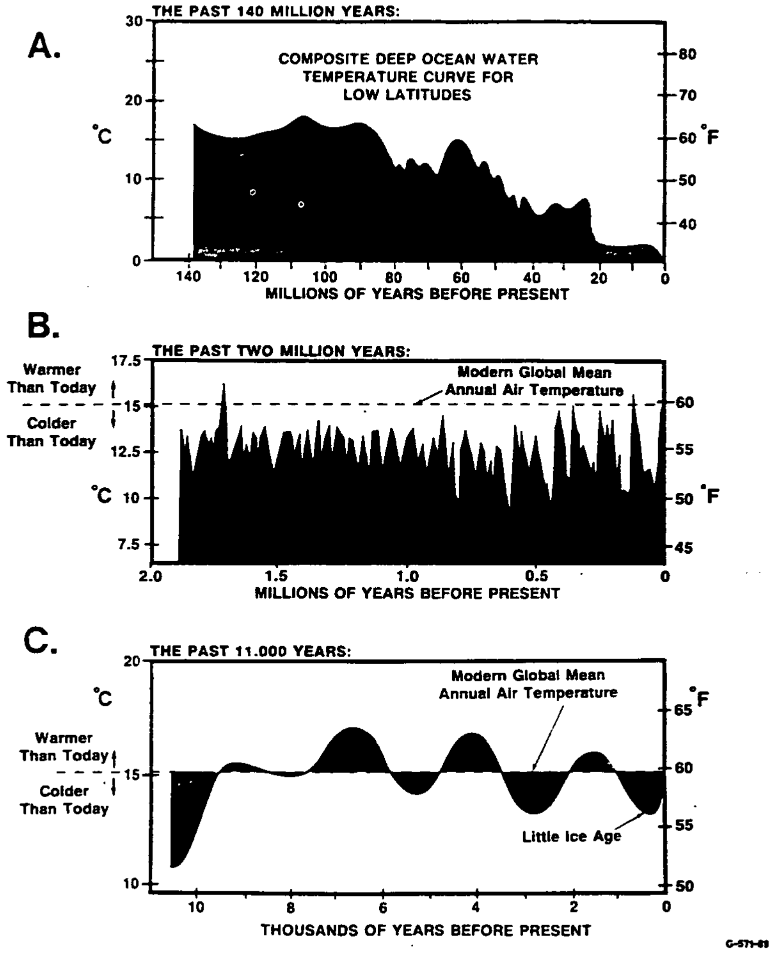
The Great Basin in the Western U.S. (primarily in Nevada, Utah, eastern California, and southeastern Oregon) is a region of dry climate today. Under the current climate regime, few lake basins within the region contain water (e.g., Great Salt Lake, Pyramid Lake). During much of the Pleistocene Epoch, (1.6 million years ago to 10,000 years ago) the climate regime in the Western U.S. was different than today. For example, during the final major glacial interval (25,000 to 10,000 years ago) of the Pleistocene Epoch many local basins within the Great Basin region contained freshwater lakes, as shown in Exhibit Board #4.

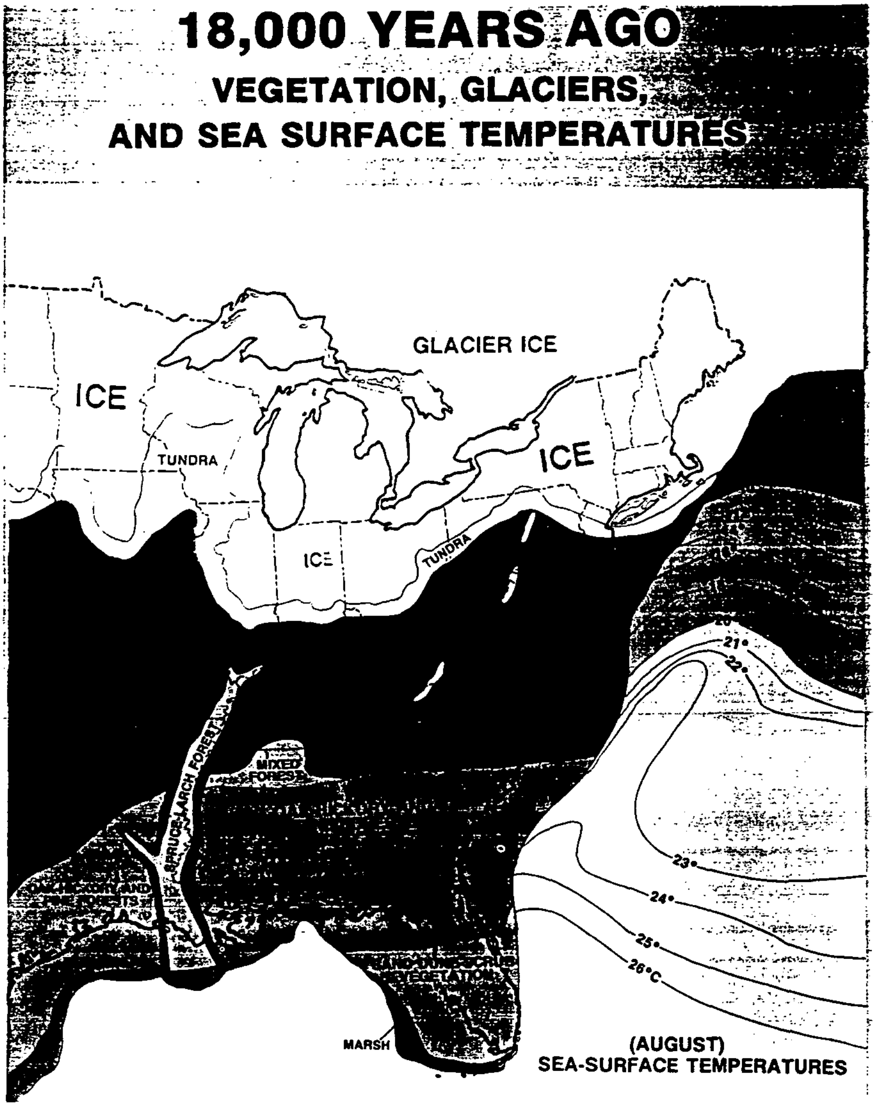
SUMMARY

The geologic record contains a valuable source of information about past climate variability on all time scales and can provide important insights into the consequences of climate change. It can tell us how individual species of organisms or entire ecosystems respond to warmer or colder climates and how fast they can respond under natural conditions. Sediment cores from lakes, marine deposits, and ice cores from glaciers contain many types of information about past climates and environments. Knowledge of this type can be very useful for testing General Circulation Models (GCM's) and for anticipating possible consequences of future climate change. For example, if one changes the boundary conditions (e.g., extent of glacier ice worldwide) of a model in accordance with known conditions at a selected interval in the past (e.g., 18,000 years ago), a GCM should be able to "predict the past" changes in atmospheric circulation that can be tested against information from the geologic record. If the model "predictions" are consistent with paleoenvironmental reconstructions, there is justification for attaching greater confidence to model predictions for future climate changes.

May 5, 1989

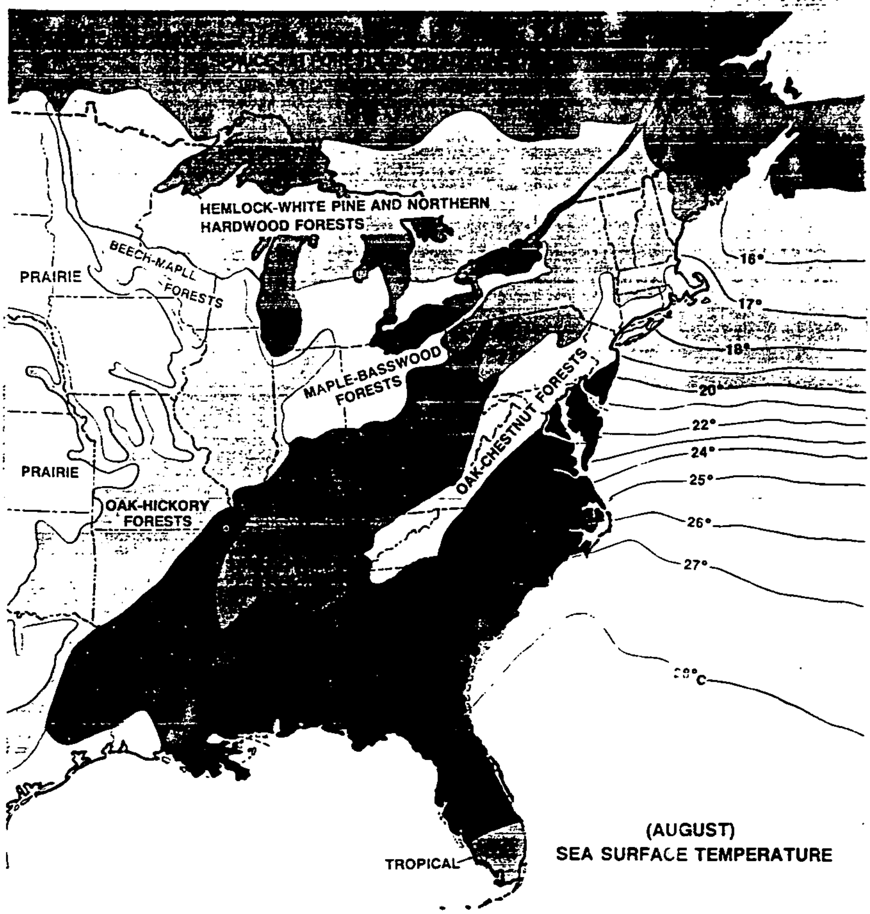
NATURAL VARIABILITY OF GLOBAL CLIMATE OCCURS ON ALL TIME SCALES



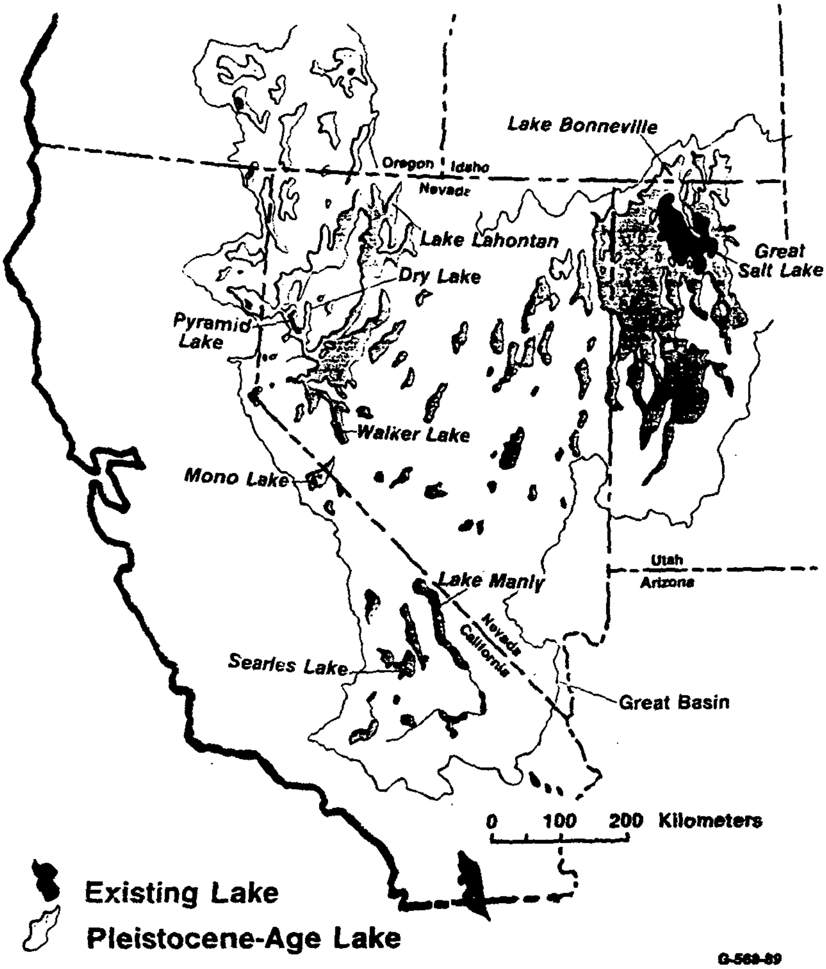

18,000 YEARS AGO
VEGETATION, GLACIERS,
AND SEA SURFACE TEMPERATURES
GLACIER ICE
ICE
TUNDRA
ICE
ICE
TUNDRA
21°
22°
MIXED FOREST
SPRUCE-LARCH FOREST
23°
24°
25°
26°C
MARSH
(AUGUST)
SEA-SURFACE TEMPERATURES

PRESENT-DAY

VEGETATION AND SEA SURFACE TEMPERATURES



GREAT BASIN LAKES DURING THE PLEISTOCENE AGE



Senator GORE. All right. Thank you very much, Dr. Peck.

Now, if you will start the clock, I will take my first round here.

One of these pictures you showed us indicated that 18,000 years ago what is now New York City was under ice, and all of New England was under ice, the Great Lakes and the Great Lakes states were under ice. How much colder was it at the end of that ice age compared to today's temperature?

Dr. PECK. About five degrees centigrade.

Senator GORE. About five degrees centigrade.

Now, Dr. Schneider, on one of your slides you showed that the global climate models indicate that five degrees centigrade is the upper range of what is now predicted to take place if we continue adding CO_2 at current and accelerated rates, and continue adding other greenhouse gases, to the point where we double the concentrations of greenhouse gases in the atmosphere; correct?

Dr. SCHNEIDER. Yes. It is at the upper range for the doubling of CO_2 if you wait a while for that to happen. But if, as you will probably here from Dr. Woodwell later, if methane or carbon dioxide came out of the dead organic matter in the soils or out of formations in which methane is trapped, that would not at all be an upper range. It could be substantially larger than that late in the next century and into the century beyond.

So it is only the upper range of the models for the doubling of CO_2.

Senator GORE. Okay.

Well, in the next panel we will explore these positive feedback loops—that is a tongue twister, but basically it means mechanisms that serves to magnify gradual trends and make them occur much faster.

Some of these feedback loops could cause us to reach the upper range of those temperatures much more rapidly than the models would indicate if we just continued with slow, gradual change, which is not gradual in geologic time.

But the point I wanted to make in this exchange is that the climate models, without these magnifiers, indicate that, within the lifetimes of people in this room, we could very well have a temperature change, with temperatures as much warmer than they were colder in this picture.

Now, if five degrees colder centigrade produced an ice age, covering a great deal of the United States with ice a mile thick, and if that change took place over thousands of years, what could five degrees warmer do in the course of a single human lifetime?

As you indicated, it is an experiment that we would prefer not to carry out, because no one can say exactly what the results will be. But the scientific models can tell us roughly the kinds of changes that we should associate with these increased temperatures and the increased concentration of gases that cause them.

Last November I was in Antarctica looking at the ice cores similar to the one you talked about, Dr. Peck. How did the ice sheet covering much of North America compare to the ice sheet now covering Antarctica?

Dr. PECK. Well, I think it was roughly comparable in size. It was about that thickness. Antarctica is bigger, as you well know, Senator; Antarctica is bigger than you might think looking at the globe. It is as big as the United States. So it is comparable.

Senator GORE. The continent is as big as the United States plus Mexico.

Dr. PECK. Yes.

If I could just note. In trying to reconstruct what the world would be like at a five-degrees-higher temperature, we do get some ideas by looking at the Earth in the Pliocene, about two and a half million years ago—the temperatures were about that. We are just starting those studies, working with the Canadians and with the Soviets.

Senator GORE. Now, at that time, what happened to the Antarctic ice sheet?

Dr. PECK. Well, the Antarctic ice sheet has been in existence since the late Eocene, anyway, some 40 million years ago.

Senator GORE. What about the West Antarctic ice sheet?

Dr. PECK. I think it was in existence then, too. Although I am starting to deal in things I do not know too much about.

Senator GORE. Dr. Schneider?

Dr. SCHNEIDER. Much less is known about the West Antarctic ice sheet. In fact, 130,000 years ago, during the last interglacial—we are presently in an interglacial, this five degree warmer state—the sea levels at some islands appear to have been as much as five meters, 15 feet or so higher than they are now. And there is speculation that the West Antarctic ice sheet had disintegrated then.

So it may come and go at much, much more rapid time frames than the East Antarctic ice sheet. We do not know how long it has been. Because the West Antarctic ice sheet is a very special case, since it has got large, thick shelves that are pinned on rises out in the ocean. And it also sticks far enough north that it is out in a warmer zone.

It is unlikely we could warm the climate enough to melt any substantial fraction of Antarctica, except possibly the west.

Senator GORE. Except the west sheet.

Now, there are two kinds of sea level rise associated with this degree of warming. The first is a relatively gradual rise in the sea level due to the expansion of sea water caused by warmer temperatures and the melting of some glaciers.

The second kind of sea level increase is a much more dramatic and sudden increase of some 12 to 15 feet, which would come from the rapid break-up of that West Antarctic ice sheet.

But let me just conclude my questions by asking you this. The increasing concentrations of gases that are found in that model, and the warming which your models predict to come as a result, are they mostly man-made? Are they mostly the result of human civilization? Or are they mostly the result of unfathomable processes of nature?

Dr. SCHNEIDER. Well, we are virtually certain, no one in science can avoid that cliche, virtually, we are virtually certain that the build up of the greenhouse gases, as you will hear from later witnesses, is due to human activities.

Because if we take a look in ice cores, the ones that Dr. Peck referred to, at the history of the gases in the atmosphere, we find that methane and carbon dioxide, the two principal greenhouse gases that people can effect, were substantially lower during the ice age, and then went up, in the case of CO_2, about 30 percent; in the case of methane, nearly doubled, due to natural causes, throughout most of our interglacial. Then, all of a sudden, looking at that ice core, somewhere around the industrial revolution in the last century or two, methane almost doubled again, and Ralph Cicerone can give you the correct numbers, and CO_2 has gone up by 25 percent.

So it seems virtually certain that the coincidence of that occurring after 10,000 years of being relatively quiet with human activities, and our knowing something about those human activities and something about these carbon cycles, leads almost everyone I am aware of, who is knowledgeable on the issue, to believe that they were caused by and will continue to grow from human activities.

Senator GORE. You must not know the nonscientists at the Office of Management and Budget.

Dr. SCHNEIDER. Fortunately not.

Senator GORE. All right. My time is up. Senator Bryan?

Senator BRYAN. Thank you very much, Mr. Chairman. Gentlemen, let me ask you, from the models that you have shown us, from the projections that you have developed, what policy conclusions ought we to draw? In other words, what action do we need to take as members of the Congress in response to these circumstances that you have outlined? Can you be specific in terms of what we can do, what options we have as a policymaking body?

Dr. SCHNEIDER. Sure, I am happy to do that. Let me just preface it by saying that listing options are things that scientists can do without adding personal values. What to choose, of course, is my own values.

The kinds of options that we can take, really, are three categories: One is engineering countermeasures. For example, some people have suggested throwing dust in the stratosphere to reflect sunlight away to counteract the warming. Mikhail Budyko, a Soviet scientist of considerable prominence, has been suggesting that for a number of years. Not necessarily seriously, but because it is possible. I have heard it also from others.

The problem with that is that I have argued there is a factor of 2 or 3 uncertainty as to what the global warming would be. So supposing you are trying to contravene a 3 degree suspected warming by putting so much dust in the stratosphere and that factor of 2 works out so that you overestimate by a factor of 2 how much dust you put in and you end up with 6 degrees cooling to counteract what really should have been 1.5 degrees warming, you would then have a problem! I think our political institutions are not quite ready for geoengineering on that scale.

Senator BRYAN. It is a bit of an uncertain option. I understand that.

Dr. SCHNEIDER. I would be afraid with all the randomness in the system as well that any time we intervene that randomness would no longer be perceived to be nature's, that it would be owned by us. There are other forms of countermeasures, though. You could freeze carbon dioxide out of stack gases and not put them directly in the atmosphere.

Of course, it takes a lot of energy to do that. The estimates I have seen suggest it would double the price of electricity, for example. Then you have to do something with the CO_2—maybe pump it in the ocean, which is where it ends up anyway, mostly, when it is put in the air.

Senator BRYAN. That is a theoretical possibility. We are not asking you to be judgmental as to cost or social impact. But that is theoretically possible.

Dr. SCHNEIDER. It is theoretically possible. There may be other tricks of that kind. Planting trees is certainly one way of taking CO_2 out of the air and not adding it to the system. To be able to counterbalance about half of the projected CO_2 from human activities over the next 50 years people have estimated that you would need to plant an area the size of Australia; and they have even tried to cost it out, and it does not stop it all.

But then we should never—let me say one more thing about policies. We should never put down any policy simply because it only solves 5 or 10 percent of the problem, because after a while, four or five of those and you have the problem half solved. So planting and reforesting is certainly one of the countermeasure solutions.

The second category of policy response is adaptation. I already said that we have probability committed ourselves to a degree or two of warming, pretty much no matter what we do short of tremendous Draconian things or short of our being completely wrong.

Therefore it would seem wise to make the investments in having the kinds of crop strains that one could put in that would be better adapted to climate futures experimented with. We need to find crops that will grow better with more CO_2.

In other words, try to take some advantage—or at least not be punished as severely as we otherwise would—by looking at these forms of adaptations. We expect water supplies to change substantially, so we might need to look at the legal baggage associated with water rights and try to find ways to make management in the future more flexible—ways to share water across regions that may be in excess by the change with those that may be in deficit.

Then finally, of course, the third policy response category, which is more severe, is prevention, and prevention could entail something as serious as altered lifestyles—we do not take as many car trips and so forth—to something less serious and I think—and now my own values come in—very sensible, which is learning how to be a more energy-efficient society. Because if you are going to use energy more efficiently then you will produce less of these pollutants.

Finally, let me just add, on a personal note in my own values, how does one choose among these various categories? I would argue, given the uncertainties, to do any action that is climate-specific is less likely to have a political constituency than one that has multiple benefits.

For example, using energy efficiently not only reduces greenhouse gases, but the fuel not burned produces less acid rain, less local effects of air pollution that is harmful to health, less dependence on foreign supplies of energy and ultimately improves our economic competitiveness. Because right now in the U.S., our manufacturing sector has about twice as much energy per value added, per unit of output as, say, Japan or the Italians, which is part of the reason why we are getting beaten on competitiveness.

So there are many reasons why energy efficiency is critical and it seems to me that if we can also get insurance, as Senator Gore said in his opening statement, against the possibility of catastrophic climate changes as part of the benefit, then that high leverage or "tie-in" strategy sets, in my personal view, an agenda that for me makes sense.

Senator BRYAN. Dr. Peck, you had a chart that showed the Great Basin indicating that it was considerably different 18,000 years ago than it is today. You showed bodies of water that no longer exist or are only remnants of what was once water. What is your projection say, 10,000 years from now? Can you share with us—is it going to be wetter, drier, or do we know?

Dr. PECK. We certainly have to worry about that to a certain extent, because of Yucca Mountain——

Senator BRYAN. Well, I did have that in mind.

Dr. PECK. We are working on that. We are having trouble enough anticipating the climate 100 years from now. Anticipating 10,000 years from now is indeed a challenge.

Senator BRYAN. Would it be fair to say that it could be much drier, it could be much wetter?

Dr. PECK. Or the same. Most of the experts, like my colleague here who look toward warmer climates, associate dryness in the center of major continents with that increased temperature.

Senator BRYAN. The bottom line is we really do not know in terms of what the climate is likely to be like 10,000 years from now. A lot will depend upon our responses—I suppose some of the options that Dr. Schneider pointed out.

Dr. PECK. Also, looking at the periodicity of glacial and inter-glacial stages over the last 2 million years have led some to presume that we are in inter-glacial that will be followed by a glacial. Maybe we should be promoting the greenhouse effect to save us from the mighty glaciers.

Senator BRYAN. My time is up. Thank you very much. Thank you, Mr. Chairman.

Senator GORE. Senator Kasten?

Senator KASTEN. Mr. Chairman, thank you. I really do not have any questions. I did not realize, Dr. Peck, how much geologists sound like economists sometimes. I was not sure if I was in the Budget Committee or the Commerce Committee.

Dr. PECK. Actually, I am trying to talk very much like a scientist.

Senator KASTEN. I just want to make a brief comment on what Dr. Schneider said in terms of where do we go from here. It seems to me that the first step we take is to stop destroying the resources that we have in place, whether it is in the Amazon or elsewhere—it is one thing to start thinking about a replanting, but right this moment we can stop the destruction of the resources and that seems to me a first step for sure.

Mr. Chairman, I do not have any questions. I look forward to the witnesses that are coming.

Senator GORE. Well, I would just like to very briefly explore a couple of other items. Dr. Schneider, if you could identify for the

Subcommittee, as you look at these climate models, which of the relationships are most salient, which have the most impact on the results coming out of the models given the different values you put into them.

Dr. SCHNEIDER. The ones that we know, are best known, are the heat-trapping capacity of the gases and how much additional radiant heat that would be trapped in the earth's surface area, surface layers. That is the good news. The bad news is, how to translate heating into temperature change, evaporation and cloudiness. The areas where we have the least skill is in trying to forecast the specific changes in clouds—do they get wider, or taller, or what—which can amplify or dampen the so-called signal by a factor of several.

Another area is sea ice. We expect if it gets warmer that we will be melting off some sea ice and that that would amplify the signal. But exactly how much and where, we do not know and then ultimately—well, there are two more.

The next one is oceans. The way we validate these models is, we take a look both backward and try to figure out what the winds were like and temperatures and so forth in ice ages and indeed, we use those to guide our understanding of how the models work.

But what we have no easy ability to validate is what happens in the oceans in the time frame of 100 years? If we heat the planet up, it is not going to warm up at the same rate everywhere. The middle of continents will warm up faster than will, say the middle of the tropical oceans, where there is about 100 meter mixed layer. That might take decades, whereas the high latitude oceans are mixed right near to the bottom, 1,000 meters or more, so it might take a century.

So what we are doing is skewing the temperature difference from land to sea and equator to pole during the transition and we simply have to calculate what that skewing is, because that skewing changes the heating patterns, which changes the anomalies that create the differences in wind patterns.

So the biggest uncertainty in my view, in terms of regional effects, is what happens in the oceans. Then finally there is the uncertainly about how biology will respond, which Dr. Woodwell will address later.

Senator GORE. Well, cutting through all of the uncertainty, would you say there is now a consensus in the scientific community that there will be warming?

Dr. SCHNEIDER. If you define consensus as saying the majority of knowledgeable people considers it a better than even bet, I would say yes, there certainly is and probably has been for a decade or so.

What we debate about is whether it is observed in the record yet and at what probability, and we debate over the kinds of details I said, but there is no one I know of who doubts the heat-trapping capacity and if you trap heat it seems fairly logical and we have almost no way to escape from the conclusion that it will be warmer.

Senator GORE. Well, we politicians are vulnerable to uncertainty. If somebody tells us that we do not really know whether the scientific evidence justifies doing something, and if the something we are called upon to do is painful or difficult, or politically costly, then we will seize on that uncertainty and say, oh my goodness, we do not know.

What you are telling us is that we do have some remaining uncertainties and there is a great deal we need to investigate much more thoroughly. And we do not know how much warming will take place. We do not know how rapidly it will occur.

But we are beginning to get better estimates of how to answer both those questions and we have seen the emergence of virtually unanimous consensus in the scientific community on the broad outlines of the problem. Human activities are intervening and overriding natural processes to produce more warming than would otherwise occur and perhaps most important of all, the warming in question will take place far more rapidly than anything nature has produced and more rapidly than we are used to responding to.

Dr. SCHNEIDER. Yes, I essentially agree with that characterization. I will just remind people that while there is a debate as to whether we have already observed this signal, in my own personal view we probably have although I do not know how to assign probability—whether it is 80 or 90 percent—because that probability is intuitive.

The only way you can prove that beyond a reasonable doubt to a consensus of scientists is to wait around another 10 or 20 years and find out that the actual system has performed the experiment according to our expectations. But the problem with waiting is simply that we will therefore have to adapt to a much larger dose of change and potential surprises than if we acted on it now and that is a value trade-off that we face and it is not a radical idea.

After all, as you stated in your opening statement, we do not know whether we are going to get in an accident or whether we are wasting our health insurance money, yet we do not wait to find out how sick we are before we buy insurance because by then they will not sell it to you.

Dr. PECK. One does have to look at this in the context of the natural variability, which is one of the things I was talking about there. So that is the unknown factor and the explanation of, why the cooling from 1940 to 1965 makes you pause and think. That sort of cooling could happen again in the future and counteract it to a certain extent.

Senator GORE. All right. With the permission and indulgence of my colleagues, we will move on now at this point. Thank you both very much. Our first panel gave us a run-down on the basic operation of these global climate models and the outlines of the problem. Our second panel is now invited to the witness table. Dr. George Woodwell, Director of the Woods Hole Research Center. Dr. V. Ramanathan, with the Department of Geophysical Sciences at the University of Chicago and Dr. Ralph Cicerone, Section Head for Atmospheric Gas Measurements at the National Center for Atmospheric Research.

Let me say in introducing these witnesses that again we are most grateful to all of you. We are going to ask you to try to keep your prepared remarks down to 10 minutes. Your complete statements will be included in the record and then we will save questions until all of you have finished your statements.

99-447 0 - 89 - 3

Dr. George Woodwell is an ecologist and a director of the Woods Hole Research Center in Massachusetts. Dr. Woodwell, we appreciate your presence here today. I have learned a great deal from your papers and have followed your work over the years. We certainly appreciate you getting us off to a good start on panel 2.

STATEMENT OF DR. GEORGE WOODWELL, DIRECTOR, WOODS HOLE RESEARCH CENTER, WOODS HOLE, MA

Dr. WOODWELL. Well, I am delighted to be here. I am thoroughly pleased that you are having this series of hearings. I am thoroughly pleased too, to discover that our governmental representatives are so well-versed in this very complicated subject.

I am a biologist and I am going to address this problem through the perspective of one who thinks about how the earth's biotic systems work. Biotic simply means, living. The dominant systems in this particular instance are terrestrial and I would call your attention to the fact that it is terrestrial exchanges with the atmosphere that determine the composition of the atmosphere in the short run.

For evidence to support that, I call your attention in particular to the set of data that Dave Keeling and his colleagues at the Scripps Institution of Oceanography have accumulated over 30 years at Mauna Loa.

Almost every citizen these days knows that famous upward-trending curve that started with the first of his work in 1958, when he developed techniques for measuring with precision the carbon dioxide content of the atmosphere. The upward-trending curve shows that carbon dioxide has been accumulating over the past 15 years, at least, at about 1.5 parts per million annually against a background that is now about 350 parts per million.

The curve also reveals a seasonal oscillation in the composition of the atmosphere. The oscillation represents a change between late winter and late summer of about 5 parts per million. That is more than 1 percent of the atmosphere. At the end of the northern hemisphere summer the concentration of carbon dioxide is lower than at any other time during the year; at the end of the northern hemisphere winter, the concentration is higher than at any other time.

The cause has been shown beyond question to be the metabolism of forests. There are various other data from around the world. My colleagues and I took several years of data from central Long Island. The amplitude of the oscillation there, where we were downwind from the large forested area in the eastern part of North America, was over several years 19 parts per million, much more than at Mauna Loa in the Pacific Ocean. At Point Barrow, Alaska, it is about 15 parts per million.

The point here is that the metabolism of forests causes that change, so if we are looking for factors that in the short term of weeks to months to years determine the composition of the atmosphere, we have to look at the terrestrial vegetation.

What happens is that during the summer the dominant process, the process that has the greatest influence on the atmosphere, is the fixation of carbon by plants. That is the process of photosynthesis. Plants—green plants—take carbon dioxide out of the atmosphere and turn it into carbohydrates—cellulose: the material of plants and other life.

During winter, photosynthesis drops and the reverse process dominates—that is respiration. Respiration is burning. In fact, its products are the same as the products of fire—carbon dioxide, heat and water. The process goes on slowly, but in the terms that we are talking about it can go on quite rapidly. In a period of weeks a substantial amount of carbon can be burned by the process of respiration.

Globally, respiration and photosynthesis on land process 100 billion tons of carbon from the atmosphere annually. The atmosphere contains about 750 billion tons of carbon. That means that roughly one eighth of the carbon content of the atmosphere runs through plants annually in photosynthesis and it runs back out annually in respiration.

Any change that affects the ratio of photosynthesis to respiration globally or regionally has the potential for changing the amount of carbon that is in the atmosphere. A 10 percent change in either of those processes will change the output by 10 billion tons.

How serious is that? Well, the 1.5 part per million build-up of carbon dioxide in the atmosphere that we see in the Mauna Loa record and see in all the other records of carbon dioxide concentration over time represents an accumulation in the atmosphere of about 3 billion tons annually.

The release from burning fossil fuels is about 5.6 billion tons annually, currently. There is an additional release from deforestation that is variously estimated that probably lies in the range of 1 to 3 billion tons. My own guess is that it is in the upper part of that range, because of the surge in deforestation recently, globally.

So a 10 percent change in the rate of respiration in a substantial region of the earth—say, the northern hemisphere, or the northern part of the northern hemisphere, where roughly a quarter to maybe a third of the total respiration of the earth is carried out, would involve a really substantial increase or decrease in the amount of carbon that goes into the atmosphere.

Now, my hypothesis is—and there is substantial evidence to support it—that the principal effect of the climatic changes that we have heard about here will be through the warming itself, that the warming will produce changes in rates of respiration. Warming increases rates of respiration and a 1 degree change in temperature commonly produces an increase in the rate of respiration of the order of 10 percent, maybe 20 or 30 percent, depending on the circumstance.

The product, of course, is additional carbon dioxide into the atmosphere and—in places where anaerobic respiration is common, which is true in many soils around the world and certainly in the tundra—methane as well. So the warming that we have already experienced has probably increased the rate of respiration of plants and soils globally and increased the release of carbon as carbon dioxide and methane into the atmosphere.

Now, I could argue that on the basis of the principles of ecology. We have done a good deal of research on the metabolism of forests and there is a reasonable basis for making the judgment that I have just made.

Second, we can go back to the really phenomenal set of data obtained from the glacial record through cores of ice. The Vostoc core, for instance, collected by a collaborative group of French and Russians through the Antarctic ice sheet, goes back 160,000 years and shows not only the temperature at which the ice was formed, but also, through very ingenious techniques developed only recently by scientists, the carbon dioxide and methane content of the air at the time the ice was laid down.

The interesting thing there is that as temperatures rose during the glacial period, so did the carbon dioxide concentration and so did the methane concentration. As temperatures dropped, the reverse occurred. Temperature and carbon dioxide and methane were correlated, albeit somewhat crudely, throughout that period.

Now, what that says is that there is a positive feedback system at work.

Now, it also says for certain that the warming and the increase in carbon dioxide in the atmosphere do not lead to the storage of that excess carbon thereby stabilizing the temperature of the earth.

So, we cannot look toward salvation in additional carbon dioxide in the atmosphere: the warming's increasing the spread of forests around the world and the storage of carbon. That may occur. But the dominant influence seems to be the opposite: the warming leads to more carbon dioxide and methane.

Now, there is a third line of evidence. If what I have suggested is correct, there should be observed a change in the amount of carbon dioxide and methane accumulating in the atmosphere in response to the warming that we have had in the 1980s.

It is difficult to prove these matters, but it does appear that the amount of carbon dioxide accumulating in the atmosphere as measured at Mona Loa and at the South Pole recently has increased from the three billion tons that I mentioned a moment ago to about five billion tons of carbon.

The carbon dioxide is going up at 2.4 parts per million on the average between Mona Loa and the South Pole as opposed to the 1½ parts per million annually that has been accumulating over the past 15 years.

Senator GORE. Since when was this change?

Dr. WOODWELL. This is over the past 18 to 20 months, and the data are from Dave Keeling, who takes those records.

Senator GORE. Oh, just so that I can clarify this, since the measurements of carbon dioxide increases began in 1957, you have observed an annual increase. There is the annual fluctuation, but each peak has been roughly 1 1/2 parts per million higher than the peak the previous year.

Dr. WOODWELL. We can say that, yes.

Senator GORE. But in the last 18 months you have measured a surge with the increase coming now at a rate of almost 2 1/2 parts per million increase from this peak over the last peak, correct?

Dr. WOODWELL. That is correct.

Senator GORE. Are you saying that this indicates a possible feedback loop that is magnifying the concentrations of CO_2?

Dr. WOODWELL. Yes. I am suggesting that the warming of the earth is increasing the rate of decay of organic matter in soils and increasing the rates of respiration of plants in general and thereby dumping carbon into the atmosphere from large pools of carbon held under biotic influences.

Those large pools of carbon globally are substantial, roughly three times the amount of carbon that is in the atmosphere at the moment.

That means that if we succeed in warming the earth enough to mobilize that carbon, we can change the composition of the atmosphere significantly, and that possibility has not been worked into the climatologists' calculations.

What it says to me is that it makes the problem, the challenge of controlling the buildup of the heat trapping gases in the atmosphere, much more acute because if things go far enough, the releases from these sources can become large enough to make it very difficult or impossible to reduce human caused releases. The releases that we have control over are fossil fuels and deforestation.

That adds an element of urgency that we have not seen before.

Senator GORE. If you could conclude your statement relatively soon, we will go on to our other two witnesses.

Dr. WOODWELL. Yes, indeed.

Well, my conclusion is, of course, that it is urgent that we move rapidly to reduce the emissions of carbon dioxide. The major sources are fossil fuels and, as Steve Schneider suggested, fairly straightforward steps toward improvements in efficiency and the use of energy have the potential for reducing the emissions in the developed part of the world by 50 percent in a fairly short time. But, it takes governmental leadership especially U.S. leadership.

Deforestation is the second point, the second place where we can touch this topic and touch it quite effectively, possibly more effectively than we think and, again, the U.S. can show leadership and must.

The third point which he also mentioned is the possibility of reforestation.

That is a much more complicated issue than it appears on the surface, but it is indeed possible and has potential for storing as much as a billion tons of carbon a year and doing it year in and year out.

We have recently addressed this issue through a conference in India, trying to engage the less developed nations in a discussion of the resources open to them.

I have here a report from that conference which might be of interest to you in due course, and I would like to give it to you.

[The statement follows:]

Biotic Feedbacks Speed the Global Warming

Testimony Before the Senate Committee on Commerce, Science, and Transportation

Monday, May 8,1989

George M. Woodwell

Woods Hole Research Center

Woods Hole, Massachusetts

I am an ecologist, President of the Woods Hole Research Center. I have worked for nearly thirty years with colleagues on studies of the biotic interactions involved in the warming of the earth. While there are clear limitations on the abilities of scientists to prove details of how the world works and to predict climatic changes or their consequences for the human enterprise, the probable consequences of failure to act now to stabilize the composition of the atmosphere and to stop the further warming of the earth due to human activities are so profound as to constitute a folly as great as global nuclear war.

The central point of my testimony is that there is a high probability that the warming already experienced is causing a further release of carbon from plants and soils globally that will speed the warming. This possibility adds urgency to the need for rapid action in moving away from continued reliance on fossil fuels, from continued destruction of old-growth forests globally, and toward management of forests that assures the further storage of carbon in an expanding standing stock of trees and soils. The steps that would be taken are salutary in any context: they lead to improved efficiency in the use of energy and move the world toward patterns of use that are economically attractive and sustainable as opposed to patterns that are leading to a cascading series of problems in our own times.

* * *

The global warming that appears to be underway at the moment can be expected to have a series of effects on the earth's vegetation and soils, especially forests, that will include the rapid release of additional carbon dioxide and methane into the atmosphere (WMO/UNEP 1985, 1986, 1988). The quantities involved are potentially large enough to speed the rate of the warming significantly beyond the limits suggested by the climatic models currently used. The magnitude of the acceleration is difficult, even impossible, to predict, but it is large enough to affect the possibilities for slowing or preventing the changes.

The potential responses of plant and animal populations to a global warming include shifts in abundance or survival of species and the interactions among species as changes in precipitation and temperature accumulate. If the changes are as rapid as currently anticipated, they will cause a wave of biotic impoverishment that is unprecedented in human history, one that will reduce substantially the capacity of the earth for support of life, including people (WMO/UNEP 1988, Woodwell 1989, TERI/WHRC 1989) . The consequences are severe enough to focus attention on efforts to slow or stop the warming.

But the most important question appears to focus on whether the climatic changes will produce effects that will slow the warming or amplify it. The answer appears to be the latter, at least as far as the biotic exchanges are concerned: the warming can be expected to speed the release of carbon in large biotically-controlled reservoirs such as forests, their soils, tundra, and swamps and bogs globally. The amount of carbon held in such reservoirs is 2-3 times the approximately 750 billion tons currently in the atmosphere. The potential of the terrestrial vegetation, especially forests, for affecting this pool is large. The exchanges are rapid, more rapid than those with the oceans, and more important in determining the composition of the atmosphere in the course of months to several years than most scientists have recognized previously.

The influence of the terrestrial vegetation on the composition of the atmosphere is best shown by data taken over the past thirty years in measurement of carbon dioxide in air. The best known set of data has been obtained at Mauna Loa in the Hawaiian Islands by Dr. C. D. Keeling of the Scripps Institution of oceanography, but there are now several other sets available, including a record that my colleagues I obtained at Brookhaven National Laboratory in central Long Island between 1965 and 1971 (Woodwell et al 1972). These records show an upward trend through recent decades at an annual rate of about 1.5 ppm of carbon dioxide in air or about 3 billion tons of carbon added to the atmosphere. But the records also show an annual oscillation that reaches a peak in April, the end of the northern hemisphere winter, and a minimum in October, the end of the northern summer.

The amplitude averaged 19 ppm over several years in central Long Island; it is about 5 ppm at Mauna Loa. The cause of the oscillation is the metabolism of forests (Woodwell 1983, Woodwell et al 1972). During winter respiration dominates and carbon dioxide accumulates in the atmosphere; during summer photosynthesis dominates and carbon dioxide is removed from the atmosphere. In the course of a few weeks the metabolism of forests changes the composition of the atmosphere by several percent. This information alone is enough to confirm the power of forests in affecting the composition of the atmosphere. The topic has been addressed in detail in various publications recently. I am including copies of recent articles that my colleagues and I have prepared to emphasize this point (Woodwell 1983, Houghton and Woodwell 1989).

Direct experimentation with the earth as a whole is generally frowned upon and we are left with reliance on inference from limited experience to anticipate the effects of warming the earth. Three lines of evidence available at the moment suggest that the warming will lead to further warming: first principles of ecology, observations of the course of the changes in the carbon dioxide content of air during the recent glaciations, and current changes in the rate of accumulation of carbon dioxide in air.

The dominant effect of the climatic changes underway, including the increase in carbon dioxide in the atmosphere, appears to be changes in the rate of respiration caused by changes in temperature. This pattern is consistent with the suggestions made in 1983 (Woodwell 1983): a one degree change in temperature changes the rate of respiration by 10-30% or more. A warming increases the rate. On a global basis the assumption is that a warming of the earth as a whole will be greater in the higher latitudes than at the equator. In the higher latitudes the warming in winter may be twice the average for the earth as a whole, thereby extending the period of decay of organic matter in plants and soils and increasing the release of carbon dioxide and methane. Because the total amount of respiration on land globally is of the order of 100 billion tons and 1/4 to 1/3 of that occurs in the higher latitudes of the northern hemisphere, the potential for stimulating a significant additional release of carbon above the approximately 5.6 billion tons from fossil fuels is great. A one degree increase in temperature in the middle and high latitudes could easily release 3-6 or more billion tons of carbon annually into the atmosphere above the amounts that were being released under earlier temperature regimes.

The second set of observations comes from experience with the Vostoc Core, a sample of glacial ice from the Antarctic reaching back 60,000 years (Lorius et al 1988). The record, carefully developed recently in one of the most important and significant technical advances in recent years, shows that during the glacial and interglacial periods the carbon dioxide and methane content of the atmosphere followed the course of temperature: as the temperature warmed, the carbon dioxide and methane concentrations rose, as temperatures dropped, the carbon dioxide and methane (MacDonald 1989) dropped as well. The record does not prove cause and effect, but it rules out the dreams of a positive feedback, the assumption, advocated by some, that the increase in temperature combined with the increase in carbon dioxide will result in the more rapid storage of carbon in terrestrial ecosystems globally, a process that would reduce the atmospheric burden of carbon dioxide and tend to stabilize the temperature of the earth. The data support instead the hypothesis of a positive feedback (Woodwell 1983).

Finally, there is the question of whether the warming already experienced has resulted in the further accumulation of carbon in the atmosphere through the stimulation of decay of organic matter on land. If so, we should expect an increased rate of accumulation of carbon dioxide in the atmosphere. Such an increase appears to be underway according to data reported recently by C.D. Keeling of Scripps Institution of Oceanography in La Jolla, California (Keeling 1989). Keeling has observed a surge in the rate of accumulation of carbon dioxide as measured at Mauna Loa and the South Pole from an annual rate of 1.5 ppm to an average of 2.4 ppm per year. The new rate applies to an 18 month period and is the type of change that might be expected in response to the warming of terrestrial ecosystems as discussed above (Houghton and Woodwell 1989, Woodwell 1983, 1989). If the increased rate of accumulation persists, the annual increment of carbon added to the atmosphere will have increased from about 3 billion tons of carbon to about 5 billion tons.

The first step in avoiding continued rapid warming globally, an ultimate necessity, is stabilization of the heat-trapping capacity of the atmosphere. Possibilities are limited. A cessation of further production of the CFC's is possible, not when convenient, but immediately. Control of nitrous oxide and methane is difficult. The major source of methane is probably the anaerobic decay of organic matter in soils, including swamps and bogs. The surge in methane production may be due primarily to the warming, although there is undoubtedly a contribution from use of fossil fuels. Nitrous oxide is thought to come from use of fertilizers in agriculture. There are probably other sources but none is easily controlled. The principal hope for control lies with carbon dioxide. What is the potential?

The potential for control lies with release from use of fossil fuels and the release from deforestation. Reforestation, if it can be accomplished on an area as large as a million or more square kilometers, might remove a billion or more tons of carbon annually. But the total potential for reductions in the emissions from elimination of fossil fuels and a cessation of deforestation is probably not more than 8 billion tons of carbon annually and the warming, if it proceeds unabated, could soon produce an equivalent amount as carbon dioxide and methane through the stimulation of respiration in terrestrial ecosystems. There is, moreover, a large reservoir of methane in clathrates that will also be mobilized as the warming progresses (MacDonald 1989).

While no scientist can predict the future course of the Earth with certainty, the indications at the moment are that the earth will warm abruptly and that the warming, if unchecked by human interference, will feed on itself to speed the warming (Woodwell 1983, 1989, Houghton and Woodwell 1989). No automatic reversal of the process is envisioned in the period of a century or two and the effects on the human enterprise are most threatening. Extraordinary steps are warranted to avoid further global warming.

Most of the following steps have been advanced previously in various meetings and documents (WMO/UNEP 1988; Canada 1989; TERI/WHRC/UNEP/WRI 1989). They are advanced again here with the additional element of urgency attached based on the observations outlined above:

Global Reduction in Use of Fossil Fuels:

A 50% reduction globally within a decade is indicated and will be followed by the need for further reductions within years. There is no alternative to abandonment of fossil fuels; the abandonment cannot happen rapidly enough to prevent a significant warming.

Cessation of Deforestation:

There are many reasons for preserving the remainder of the world's old growth forests, but their destruction at the moment is a major source of carbon dioxide and methane for the atmosphere. The problem is global; it applies to all nations including the United States and all forests, including the Tongass.

Reforestation:

Reforestation is always difficult and uncertain of success. But extraordinary efforts are warranted around the world in reclaiming land for forests. the land available is probably impoverished kin most instances and research may be needed to determine how to proceed.

Alternative Sources of Energy:

Research and development will be needed and subsidies will be appropriate to advance alternatives such as the following to current uses of fossil fuel energy:

- -improve efficiency in all uses of energy, including automobiles, heating, lighting, energy generation and transport;
- -conservation of energy;
- -biotic sources of energy and their management;
- -solar technologies, including air, water and electricity (photovoltaics);
- -hydrogen as a fuel for transportation;
- -ocean thermal energy;
- -mass transportation: to the extent that mass transport saves energy, it is a source of energy.

Basic Research in Ecology:

The density of human activities has reached the point where the biotic basis for support of life is being undermined globally. Research on that and related topics has languished over recent decades as money has been funneled into biomedicine, biotechnology, physics and deflected otherwise into military expenditures. It is time now to refocus attention on the basic science of environment, address the difficult questions of how to stabilize populations and how to use resources renewably. It is also time to see that the basic information about the earth becomes a part of the working knowledge of every citizen. Specific topics that require support include:

1. A Global Forest Inventory Using Satellite Imagery: Imagery exists but must be applied to the purpose of measuring the area and rates of change in the area of forests globally. No federal agency has been willing to develop or support such a program despite the importance of the data to appraisals of the emissions of carbon from deforestation and to estimates of the rates of biotic impoverishment globally.

2. The Structure and Metabolism of Terrestrial Ecosystems: How will the climatic changes affect various terrestrial systems around the globe? The topic requires both experiments and extensive monitoring.

3. Biogeochemical Cycling With Emphasis on Carbon.

4. The Processes of Biotic Impoverishment and How to Prevent and Reverse It.

5. The Requirements for A Sustainable Society, Locally and Globally.

6. Regional and Local Planning to Stabilize Landscapes and Prevent Impoverishment in Both Tropical and Temperate Zones.

Progress in these directions is unlikely until the federal budget has been balanced. Meanwhile, these and other urgent topics languish and the world, looking appropriately for leadership from the largest and most progressive nation in the world, watches the problems become compounded and more expensive to resolve.

References and Notes

Houghton, R.A. and G.M. Woodwell, 1989. Global Climatic Change. Scientific American. April. pp36-44.

Keeling, C.D. 1989. Personal Communication

Lorius, C., N.I. Barkov, J. Jouzel, Y.S. Korotkevich, V.M. Kotlyakov, and D. Raynaud. 1988. Antarctic ice core: CO^2 and climatic change over the last climatic cycle. Eos 681-6784

Mac Donald, G.J. 1989. Personal Communication

TERI/WHRC/UNEP/WRI, 1989. Conference Statement: Global Warming and Climate Change: Perspectives from Developing Countries. Tata Energy Research Institute, New Delhi; Woods Hole Research Center, Woods Hole; United Nations Environment Programme, Nairobi; and the World Resources Institute, Washington. 39 pp

Woodwell, G.M. 1983. Biotic effects on the concentration of atmospheric carbon dioxide: A review and projection. in Changing Climate, NAS Press, Washington DC

WMO/UNEP, 1985. Conference Statement: International Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, Villach, Austria, October 5.

WMO/UNEP, 1986. Report of the International Conference on the Assessment of the Role of Carbon Dioxide and Other Trace Gases in Climate Variations and Associated Impacts. Villach, Austria October, 1985. WMO 661, 78 pp

WMO/UNEP, 1988. Developing Policies for Responding to Climatic Change: A summary of discussions and recommendations of workshops held in Villach and Bellagio, 1987. 53 pp.

CONFERENCE ON GLOBAL WARMING AND CLIMATE CHANGE

Perspectives from Developing Countries

CONFERENCE STATEMENT

1. A RAPIDLY WARMING EARTH AND RISING OCEANS

1.1. Global warming is the greatest crisis ever faced collectively by humankind; unlike other earlier crises, it is global in nature, threatens the very survival of civilization, and promises to throw up only losers over the entire international socio-economic fabric. The reason for such a potential apocalyptic scenario is simple: climatic changes of geological proportions are occurring over timespans as short as a single human lifetime. The World Bank, regional development banks, and other development assistance agencies will need to reappraise their policies in light of the impending global warming. In particular, developing countries will need assistance in the transition phase from traditional fossil fuels to more appropriate energy forms, and in promoting the preservation of forests and reforestation.

1.2. Certain atmospheric emissions resulting from various human activities are unambiguously responsible for this crisis. They include carbon dioxide - the necessary product of combustion of fossil fuels, CFCs (chlorofluorocarbons) from refrigeration and halons from firefighting systems, methane from the anaerobic digestion of organic matter, and nitrous oxide from increased use of chemical fertilizers. The problem is compounded by deforestation which contributes to increased carbon dioxide and other greenhouse gases emissions due to wood combustion, as well as to decreased carbon fixation in biomass due to reduced tree cover. These gases absorb and partially trap the heat radiated by the earth, reradiate some of it back to the surface, and this leads to a warming of the lower atmosphere. The current global heat balance is thus upset and leads to a warming of the earth's surface. Scientific meetings in 1985-87 at Villach, Austria and Bellagio, Italy, were critical in developing an updated scientific consensus on global warming.

1.3. The World Commission on Environment and Development, in its report, called upon governments "to initiate discussions leading to a convention..." on measures to limit global warming and sea level rise. The Commission added that "if a convention on containment policies cannot be implemented rapidly, governments should adopt contingency strategies and plans for adaptation to climate change."

1.4. The UN General Assembly's first debate on "Our Common Future" in October 1987 was marked by references to global warming dramatized by a plea from the President of the Republic of the Maldives for international action to prevent the disappearance of his nation beneath rising sea levels.

1.5. Presently, the contribution of carbon dioxide to global warming is roughly fifty percent; the other half is due to the other gases (methane, CFCs, nitrous oxide, etc.). These latter gases are one thousand to ten thousand times more effective than carbon dioxide and consequently are dangerous even at their present trace concentration levels.

1.6. In addition, positive feedback effects are very important in global warming. A consideration of the interactions of warming with the large biotically-controlled pools of carbon on land suggests that there will be further release of carbon dioxide and methane from these sources with an increase in temperature. The cause of this additional release is the stimulation of the respiration and the decay of organic matter. Over the past fifteen years, the rate of accumulation of carbon dioxide in the atmosphere has been about 1.5 ppm per year. However measurements conducted over the past 18 months indicate that the rate has increased to 2.4 ppm. This is consistent with the positive feedback hypothesis.

1.7. The atmosphere is already committed to a warming of 0.7 to 2 degrees C due to the emission of greenhouse gases up to the early eighties. At current rates of emission, committed global warming will increase by 0.2 to 0.5 degrees C every decade, and by the end of this century, the cumulative surface warming will be large enough to rise above the background climate fluctuations. Much of the committed warming due to current emissions will be stored in the oceans and will show up in the atmosphere several decades later. However, this can lead to an upsetting of the temperature gradients in the world. Consequently, wind and ocean currents, and precipitation patterns will be affected. The higher temperatures will also lead to a rise in the sea level. Sea level rise of the order of 5 to 24 cms per decade can be expected as against the background increase of the order of 12 cms per century. This implies that coastal areas presently less than 1 to 3 meters above the sea level will be threatened by the middle of the next century. The most-affected areas would be the river deltas which are also the most populated areas in the world.

1.8. Thus human activities have opened an era of rapid climate changes that, if unchecked, promise an extraordinary reduction in the potential of the earth to support a reasonable quality of life for all.

1.9. This topic has been reviewed recently in several international conferences. The conclusions have universally pointed to the need for early action to deflect or stop these climatic changes. The WMO/UNEP scientific conference at Villach, Austria in 1985 and the Villach-Bellagio meetings of 1987 both expressed the extent of the consensus that exists among scientists that the warming will proceed rapidly and presents a serious threat to the human race. The Canadian Conference on the Changing Atmosphere held in Toronto in June 1988 produced a clear and detailed statement that drew on the earlier conclusions to call for early action to reduce emissions of carbon by reducing use of fossil fuels and by improving management of forests. The purpose was to reduce rates of change of climate in the next decade to rates similar to those experienced over recent centuries. All of these discussions of both effects and potential corrective actions have recognized the special interests of the developing nations.

1.10. This conference is the first arranged to address the particular concerns of the developing nations, which are struggling to improve the standards of life of their people. Nearly 4 billion of the present human population of 5 billion live in developing countries. They need accelerated economic growth but on an ecologically sustainable basis. It is against this background that the participants of the International Conference on "Global Warming and Climate Change: Perspectives from Developing Countries", who met at New Delhi, India, from February 21 to 23, 1989, present the following analysis and recommendations.

2. THE NATURE OF THE PROBLEM

2.1. There are three distinctly different but strongly inter-related parts of the problem: (i) Global chemical pollution; (ii) The greenhouse effect of these pollutants; (iii) The global climate change, resulting from the greenhouse effect induced by the pollutants. Significant scientific progress has been made in understanding and observationally documenting many of these effects. This progress had led to an international consensus among scientists on the significance and the seriousness of the potential global scale warming and the accompanying rise in sea level. The predicted warming rates for the next several decades are unprecedented in terms of climate changes of the last several thousand years.

2.1.1. Global Chemical Pollution:

Instrumented observations of the air have demonstrated that:

(1) The concentrations of several gases, such as: Carbon-dioxide; Methane; Chlorofluorocarbons amongst several others, have increased significantly during the last century and are continuing to increase substantially.

(2) The increases in the pollutants are caused by a variety of human activities including:

- Fossil-fuel combustion
- Other industrial activities
- Deforestation, biomass burning, and the accelerated decay of organic matter in the soil

(3) The pollution is global in extent and spreads through the strata of the atmosphere.

2.1.2. The Greenhouse Effect of the Pollutants:

(1) The gases trap the heat radiation from the earth, and hence, the observed rise in the gas concentrations has increased the heat trapped in the planet. This so-called greenhouse effect is a well understood phenomenon and is based on sound physical principles.

(2) Until the 1960's, carbon-dioxide increase was the major source of heating. This picture has changed dramatically in the recent decades during which several non-carbon dioxide gases contributed as much as carbon dioxide to the increase in the planetary heating.

(3) Thus as time goes by, the problem is getting not only larger in magnitude but more complex in character.

2.1.3. **Global Warming and Climate Changes:**

(1) The most direct effect of the increased trapping of heat radiation is a global warming.

(2) The warming will not be globally uniform but will differ significantly between geographical regions; in addition, the warming may vary during different seasons. As a result, the altered temperature gradients will alter the pattern of winds and precipitation distribution regionally. The details of these localized changes are not clearly understood.

(3) The observed global temperature records, that include ocean and land temperatures, reveal a warming trend during this century; the magnitude of the warming trend is within the range predicted by models. Furthermore, the latter half of the decade of the 1980's registered the warmest temperatures on record.

(4) The warming of the oceans, as well as the melting of ice sheets and glaciers resulting from the warming of the land will lead to a rise in the sea-level.

2.1.4. **Major issues that need to be resolved:**

(1) Biosphere - climate interactions:

The biosphere controls the atmospheric concentration of greenhouse gases like CO_2 and CH_4, and biotic processes like respiration are regulated by temperatures. Interactions between the biosphere and climate can play a significant role in determining the future concentrations of greenhouse gases like CO_2 and methane.

(2) Cloud - climate interactions:

One of the largest sources of uncertainty in predictions of regional and global climate changes is the response of clouds to the warming. The tropical monsoon cloud-systems are one of the biggest factors that regulate the global heat budget and these clouds respond significantly to small changes in ocean temperatures. There is an important need for a focussed analysis of this problem.

(3) Future atmospheric concentrations of greenhouse gases:

Another large source of uncertainty is the rates of future increase in the concentrations of the greenhouse gases. This will depend on the scenarios adopted for future energy demands and supplies and other human activities.

(4) Deforestation, biomass burning and emission of particles:

We have to assess how these localized changes, which have a profound influence on the regional climate, interact with the global scale warming effect of the gaseous pollutants.

(5) The role of the oceans:

The oceans play a dominant role in governing the timing and the rate of the warming, because of the enormous heat capacity of oceans compared to the land. We are at the very early stages of understanding the interactions between the greenhouse warming and the dynamics of the oceans. Significant improvement in understanding this problem is needed to improve the predictions of regional climate changes.

3. POTENTIAL IMPACT

3.1. Global Warming is occurring at a time when many of the world's life-support systems are already stressed by the growth of population, industrial development and need for agricultural land and the unsustainable exploitation of natural resources. These stresses are caused both by careless and short-sighted actions and as a consequence of poverty and underdevelopment. They include increasing air and water pollution, deforestation, soil erosion and salination, among others.

3.2. A disregard for long-term consequences of industrial development and population expansion have resulted in air and water pollution, deforestation, and soil erosion among others.

3.3. On all of these changes, global warming and associated climate change will bring additional consequences, such as:

- higher temperatures
- changes in precipitation and storm activity
- widespread run off
- reduction in fresh water availability
- global rising of mean sea level

3.4. Consequences

3.4.1. The consequences of these climate changes will affect every aspect of society and the material environment. Their impacts will cause a strain particularly in developing countries, where already, in many cases, existing conditions already allow for only marginal existence for both people and ecosystems.

Areas of particular concern include:

- agriculture
- water availability
- human health
- human habitation
- natural ecosystems, including biological diversity.

3.4.2. Global food supplies may be maintained through shifts in productive regions and technological advances. However, changes in local production and food distribution may aggravate circumstances which are already unacceptable in some areas, particularly in low latitude regions where precipitation is already highly episodic.

3.4.3. Sea-level may rise above one meter within the next century, which is about eight times as fast as occurred over the last century. Since already 70% of the world's coastlines are eroding, this problem will aggravate an already difficult situation in many areas where half the global population resides.

Effects of sea-level rise include:

- loss of land and human habitation
- penetration of salt into drinking and agricultural water supplies
- beach erosion
- loss of wetlands and wildlife habitat, including air fauna
- damage of infrastructure including harbors, cooling water facilities, coastal defense systems, roads and other infrastructure

Lower latitude coastlines, frequently found in developing countries, are particularly vulnerable to these effects due to the particular morphology of these coastlines.

3.4.4. Island states would be particularly vulnerable to sea level rise and are in grave danger of facing serious climate aberrations long before the sea level rises to a point of total submergence.

3.4.5. Tropical storms may occur with greater intensity and will certainly penetrate further inland due to sea level rise, resulting in greater loss of life.

3.5. Ecosystem

3.5.1. Sea-level rise will devastate coastal ecosystems such as mangrove seaways, which no longer migrate inland because of human habitation near the coast.

3.5.2. Terrestrial ecosystems will need to move poleward in response to the warming. However, the rate of warming may exceed the ability of ecosystems to migrate, (or cooridors of migration may not be available); so loss of species or reduction in numbers can be expected.

3.5.3. In particular, canopy forests may suffer substantial declines.

3.5.4. Loss of carbon from forests and soils due to increased respiration and reduced biomass would add substantially to the build up of CO_2 and thus to the rate of warming.

3.6. Human health

3.6.1. Direct and indirect consequences of climate change such as increased air and water pollution, spread of tropical disease vectors and decreased fuelwood availability have important consequences for human health.

3.6.2. Since climate change and rising sea-level will occur at rates which far exceed historical values, adjustment to these changes will be difficult and costly for human societies in the less developed countries.

4. THE NEED FOR ACTION: INITIATING APPROPRIATE RESPONSES

4.1. As the foregoing findings indicate, the buildup of greenhouse gases in the atmosphere threatens societies and natural environments in fundamental ways. While significant uncertainties remain, particularly in characterizing the timing and seriousness of regional effects, available information is more than sufficient to justify responsive actions by governments and others. Political leaders and the public should treat the prospect of global warming and adverse climate changes with utmost seriousness and act accordingly. Under the circumstances, governments and others should begin the process of planning and implementing a concerted international response that will require major actions and cooperation on the part of all nations.

4.2. It is sometimes said that it is too early to act on global warming. A more accurate appraisal appears to be that societies are already late in responding. It is also said sometimes that a little warming might be beneficial. It seems very likely that the issue is no longer a little warming - the earth if probably already committed to that. The issue now is how big a warming?

4.3. It is not difficult to sketch the general contours of what must be done to contain the greenhouse warming. Societies should act aggressively on an international basis to do the following:

4.3.1. Increase sharply the efficiency with which fossil fuels are used; the technology is available today to do this;

4.3.2. Introduce non-fossil energy technologies on a priority basis. The principal available candidates are renewable energy sources and nuclear power; the choice between them is sure to be hotly debated;

4.3.3. Phase out CFCs completely in this century; the technologies are being developed to do this; steps should be taken to ensure that such technologies are available to developing nations on non commercial terms as soon as they are ready for commercial use.

4.3.4. Promote a large-scale international effort to halt deforestation in the tropics and move to net forest growth globally; and

4.3.5. Stabilize world population well before it doubles again.

4.4. Other steps are also needed. Natural gas is preferable to oil and coal as a transitional fossil fuel. Traditional pollution control measures can reduce nitrogen oxide and hydrocarbon emissions.

4.5. Beyond this general list, there are immense complexities in deciding exactly who should do what, when, and how. When we consider the greenhouse issue, we find an important asymmetry. While the great bulk of past and current emissions of greenhouse gases have come from the highly industrial nations, it is possible that many of the most serious effects of global climate change will occur in the developing countries.

4.6. A number of factors would likely produce this result: (1) developing countries are many times more dependent on natural resources and natural systems (including crop and grazing lands, forests, fisheries and monsoon patterns), and these natural systems are heavily dependent on climate; (2) the poorer countries, already stressed by other problems, lack the financial and technical resources to make the expensive and difficult changes that adapting to climate change would require; (3) many developing countries have particular vulnerabilities, such as vulnerability to rising sea levels and to "natural" disasters such as floods, droughts, and unusually powerful storms or other weather events, which could increase as a result of the greenhouse warming; and (4) climate disruption in developed countries will lead to a serious threat to global food security, since traditional bread basket countries may not have much surplus left for export either on concessional or commercial terms.

4.7. Clearly the first and largest response to the global warming threat should come from the industrial nations. They should not wait on international agreement to begin a major effort to increase energy efficiency and reduce wasteful fossil fuel use. The industrial countries have the primary responsibilities for reducing use of fossil fuels and CFCs and for committing major economic, technological and political resources to this issue.

4.8. Despite the prominence of the industrial countries in bringing on this global problem, the contribution of the developing countries is already significant and is projected to grow in the future. Today, about twenty percent of the emissions of the principal greenhouse gas, carbon dioxide, is estimated to be coming from fossil fuels used in developing countries. By the middle of the next century, this figure could climb to well over 50 percent. While historically the developed countries have a record of large scale deforestation, today carbon dioxide emissions from deforestation (perhaps 20 percent of the total) come largely from the developing countries.

4.9. The developing countries' contribution in response to the greenhouse challenge should be carried out in a way that enhances, rather than diminishes, development prospects. Where these are in conflict, priority should be given to development, which brings so many clear and needed benefits, particularly for the poorest 60% of the population in developing countries. Only in this way can these populations be brought to the minimal level of health and resilience needed to cope with environmental stress and stabilize population sizes.

4.10. When resources are inadequate for mounting programs both for needed development of the poor and achieving globally desirable reduction of greenhouse gas emissions, developed countries should be asked to contribute the difference. Climate protection should be seen as a challenge to be met in partnership with the development assistance community and the industrial countries and not simply as another problem for the developing world. Having caused the major share of the problem and possessing the resources to do something about it, the industrial countries have a special responsibility to assist the developing countries in finding and financing appropriate responses.

4.11. The challenge before us, that of global warming of the magnitude projected today, cannot be met without the full participation, in equal partnership, of the developing world. They are potential contributors in future and burden-sharers today, for, their development - sustainable growth - depends in a crucial way in planning ahead in the right way.

CONFERENCE ON GLOBAL WARMING AND CLIMATE CHANGE

Perspectives from Developing Countries

4.12. Development of options for responsible action and the successful implementation of internationally-agreed steps both require that the developing countries take part in the debates today - scientific, socio-economic and political - and in the negotiations ahead.

4.12.1. The participation has to be at least at three levels:

1. Public: The public needs to know what is going on. The help of discerning media and women's groups and NGO's, especially in the developing world is important here.

2. Individual or group research efforts: Individuals and groups with expertise in research should be encouraged to undertake relevant scientific and policy research and studies. Their interaction with their counterparts in other countries should be encouraged.

3. Government(s): Must receive expert advice and analysis, for their role is critical for negotiations and action.

4.12.2. The responses of the developing countries should be in the following areas in particular:

- **improving energy efficiency.**

  Studies have shown that both industrial and traditional sectors of developing country economics can be inefficient users of energy resources.

- **pioneering renewable energy use.**

  The developing countries have the potential of being on the forefront in the use of solar energy, biofuels, and other renewable technologies, all of which should grow sharply on a global basis in the years ahead.

- **moving to net forest growth and halting deforestation.**

  This will require major international cooperation and additional financing, perhaps including international arrangements through which debt relief is exchanged for forest conservation.

- **slowing population growth.**

  The greenhouse warming challenge is but one of many that will be more tractable in a world of modest rather than explosive population expansions.

4.13. To arouse the people of the world to the danger of the greenhouse effect, the available data and audio-visual documents needs to be employed extensively. The major responsibility towards this action rests on developed countries and also, on informed persons from developing countries - and these two groups can cooperate.

4.14. These and other steps needed to address global warming are justified by concerns apart from climate change. They will produce many benefits beyond protecting the earth's climate: saving the earth's protective ozone layer, promoting sustainable development and preserving the biological wealth of the tropics, reducing urban air pollution and acid rain, enhancing energy security, and perhaps most important, demonstrating that the nations of the world can work together on a matter of great importance.

5. THE INTERNATIONAL PROCESS

5.1. Because climate change is a truly global problem it requires global solutions, involving cooperative actions by all countries. Implicit in this is the necessity for differentiated responses by industrialized and developing countries. Industrialized countries will need to take earlier remedial actions and to assist developing country efforts, in particular through resource and technology transfer. The World Bank, regional development banks, and other development institutions will all have to be involved.

5.2. An international process is, in fact, already under way on several fronts. In the realm of science, the International Council of Scientific Unions (ICSU), with the cooperation of WMO, UNEP and UNESCO, has launched the International Geosphere-Biosphere Program (IGBP), which represents an integrated scientific approach to problems of global change. In addition, various national scientific research efforts on greenhouse gases are also being coordinated through WMO and UNEP.

5.3. On the diplomatic front, WMO and UNEP have sponsored the Intergovernmental Panel on Climate Change (IPCC), which is to develop a comprehensive initial assessment of the scientific evidence and impacts of climate change, and strategies for policy response. This assessment is expected to be completed by August 1990. A Maltese initiative at the 1988 UN General Assembly gained global support as an expression of international concern over the problem and, of particular relevance, called for the initiation of work in international legal instruments to address climate change.

5.4. In addition to governments and multilateral institutions, non-governmental organizations are playing an important role in the international process. Meetings in Toronto, Washington D.C., Woods Hole, Turin and now in New Delhi, and planned conferences in Brazil and Egypt, all contribute to an exchange of information and to sensitizing public opinion and policy makers to the dimensions of the climate problem and the needed responses. The media has a very important role to play and these meetings should seek opportunities to reach the public through the press, radio and TV. As demonstrated by some initiatives, such as the Turin Conference, public understanding and awareness on global warming can and must be further developed. The task is to provide sound information on the state of scientific knowledge and on action that should be taken not only by decision makers but also by the public at large.

5.5. A unique characteristic of the international response to climate change is the essential linkage between science and policy. Because of the complexities involved and the many different sectors in which actions are required, there is no single solution or technological quickfix. The problem will need to be disaggregated and partial solutions sought -- as exemplified in the 1987 Montreal Protocol on protection of the ozone layer. Recognizing that policy decisions will have to take place under conditions of scientific uncertainty, it would be desirable and practical to aim for interim decision points for policy actions based on the best available scientific evidence and consensus. If nations delay actions in an elusive quest for scientific certainty, the risks and costs will mount unacceptably. In order to attain quick results, industrialized countries should adopt regulatory measures immediately and support developing countries with resources and technology so that their future contribution to global warming is curtailed. Equitability should be the key component of such decisions, if they are to be accepted wholeheartedly by the developing nations.

5.6. Coordinated international policies can be developed through negotiations leading to international conventions to promote research, monitoring and exchange of data. Such agreements should be supported by protocols which address specific remedial actions in such areas as reduction of CO_2 and other trace gases, energy efficiency, renewable energy sources, technology transfer, and the deforestation problem.

5.7. Particular note should be made of the role of women in the developmental process. In many countries, including India, women are already playing an essential role in addressing issues relevant to climate change. Women's organizations are active in family planning, energy conservation and efficiency, afforestation programmes, and use of renewable energy (e.g. biogas, solar cookers etc.). As women are on the front line of development efforts, their particular insights and perspectives need to be sought at both the community and the international levels.

6. PERSPECTIVES FROM DEVELOPING COUNTRIES AND AGENDA FOR ACTION

6.1. Action by Developed Countries

It is the perception of the participants of the conference that the industrial countries, being primarily responsible for increased concentration of carbon dioxide and other greenhouse gases in the earth's atmosphere, must take immediate steps to reduce further increases in the level of carbon dioxide emissions. Actions to be taken by them must cover:

6.1.1. Improvements in energy efficiency - The record of the last 16 years within the OECD countries has been most heartening and in some cases spectacular. However, there is evidence that the momentum of energy conservation is slowing down as a result largely of decreased energy prices. Governments must institute a system of incentives and disincentives for bringing about rapid and further improvements in energy efficiency in these countries.

6.1.2. In order to promote energy efficiency and alternative energy sources, fees or taxes must be imposed by the developed countries on the emission of greenhouse gases from fossil fuel use. In this respect, several developing countries have followed very heavy taxation measures, resulting in high prices of petroleum products in particular. This contrasts with the short-sighted decline, particularly in gasoline prices in several western countries, which would only bring about larger increases in private transport, an expanding fleet of gas-guzzling automobiles and a slowing down of public transportation developments. This situation must be reversed through a determined implementation of a new fossil fuel tax regime. Undoubtedly, some of these measures will have adverse regional impacts, such as on coal producing regions, but local solutions and support will need to be found for a smooth transition to lower fossil fuel production in these locations.

6.1.3. The proposed tax on greenhouse gas emissions should provide finances for measures that can protect global climate. Such funds should be used for:

1) Large scale research, development and demonstration activities related to renewable energy technologies;

2) Transfer of energy efficient technologies from the developed to the developing countries;

3) Financing of forestry and other projects in parts of the world where availability of large scale deforestation calls for immediate measures.

6.2. Public Policy Needs in Developing Countries - Options and Investment Decisions

The developing countries must evaluate a range of public policy options that may contribute towards the global effort in countering the greenhouse effect. Unfortunately, not enough research and analysis have been carried out on the economic costs and benefits of the options available, and actions will have to be preceded by adequate analysis in the immediate future.
Hydropower potential has not been fully utilized in the developing countries. Development and exploitation of such resources is till lagging behind because of large investment requirement for infrastructure, submergence of habitats and environmental problems associated with hydro, but also because of easier options provided by fuelwood and coal. Efforts to develop and utilize hydropower potential on ecologically sound lines should be encouraged and can be assisted by multi-lateral financing of infrastructure. The public policy needs of the developing countries are related to the following areas:

6.2.1. Involvement of local, regional and national governments in understanding the nature of the greenhouse effect and its possible impacts - In essence, actions and policy initiatives can only be mounted and sustained provided there is adequate public awareness of the whole subject area. Hence, researchers and policymakers at various levels need to interact closely in the years ahead.

6.2.2. Adjustment of energy policies and investment priorities - With the growing capital intensity of energy supply all over the world, it is unlikely that governments would be able to support expensive energy development programmes just because they may be beneficial in reducing carbon dioxide emissions. However, there are a range of viable options which are desirable from the development and welfare perspective, but the inertia of organizations and on-going programmes have not come fully to grips with some of these options. As newly industrializing nations add to their energy infrastructure, they have the advantage of being able to choose those technologies that follow efficient end-use strategies that minimize the risk of climate change and which promote sustainable economic development. Many of the efficiency solutions are also more cost effective than equivalent supply options. These would typically involve:

(1) An increased development of renewable energy technologies which are already viable for specific applications and regions in the developing countries. It is particularly important to provide R&D programs in this area with a goal orientation and to bridge the gap between lab results and their widespread applications. It is also important to ensure that conventional energy supply industries accept and introduce renewable energy options wherever they are economically viable.

(2) Regions and local communities within developing countries must develop biomass related energy plans which cover a whole range of biomass production, conversion and utilization options, which again would not only address the needs of the largest sections of society in several developing countries, but would also ensure greater absorption of CO_2 through plant growth, quite apart from providing a means for arresting the degradation of large areas of land.

(3) Natural gas is being found on a large scale in several parts of the developing world, but decision making processes to utilize natural gas as a fuel are still tardy, partly because of large investment requirements for infrastructure, but also because of competing uses such as for fertilizers and petrochemical products. The use of natural gas as a fuel again is not only desirable from the point of view of global warming, but also because it is often the most attractive economic option in energy development. Efforts to utilize larger quantities of natural gas can be assisted by multi-lateral financing of infrastructure and greater trade in natural gas among the developing countries.

(4) In the immediate future, developing countries may have no choice but to pursue larger production, distribution and use of petroleum products. This would be particularly desirable where coal is being used on a large scale and in those regions where fuelwood is the main cooking fuel. In essence, a shift from fuelwood and coal towards oil would generally be a desirable policy option.

(5) Energy policies need to be developed on a sound quantitative base, and developing countries may consider the use of suitable quantitative models which could evaluate future policy options including environmental and CO_2 implications. Policymakers would then be able to articulate energy policy on a more rigorous basis.

6.2.3. Afforestation - The rational for extensive afforestation already exists in strong measure in most developing countries, particularly where forest area has dwindled in recent years. The problem of CO_2 concentration levels only adds greater urgency to this sector. Several policy actions can be identified in respect of afforestation:

(1) Increased outlays on afforestation are highly desirable including support from international donors and multi-lateral organizations.

(2) Extension programmes to promote agroforestry by farmers themselves need to be mounted on a large scale, so that forestry can be made a success story like agriculture through the participation and involvement of private sector farming which is in the hands of several billion people in the developing countries.

(3) Some of the larger countries in the world have to come to grips with a clear grazing policy and an overall strategy for controlling animal populations, which are often a burden on the land and impose a net cost on society. The long run strategy for improvement of cattle breeds and reduction of their populations requires vigorous implementation.

(4) In respect of animal grazing and the whole sector of forestry, a major thrust towards community involvement is long overdue. Forestry organizations need to move afforestation programmes closer to the people to ensure their fullest participation and success of governmental efforts.

(5) An intensification of science inputs, particularly in respect of biotechnology research and extension networks to improve the scientific base of forestry programmes would not only make investments in this sector attractive for farmers and private organizations, but also help to increase yields from limited land areas.

(6) Afforestation policies particularly in relation to peoples' participation and awareness programmes must be examined and improved. Social aspects in promoting afforestation also need deeper investigation and attention.

(7) Utmost efforts must be made to abate the global warming and consequent sea level rise. However, significant sea level rise may take place despite all the above measures. Vulnerable people in the coastal areas will be affected and vast areas will be inundated. People in those areas will strive to develop their coping strategies and adaptations in their livelihood systems. Investment and support would be necessary to enable affected people to develop these coping strategies.

6.3. Research Training and Development: Imperatives and Priorities

6.3.1. Research and development efforts have to be tailored to achieve the twin goals of mitigating the continued increase in greenhouse gas accumulation and adaptation to its consequences.

6.3.2. For both these purposes, the dimension of ecological sustainability needs to become central to all research and development strategies and activities. For this, we need reliable tools and indices for measuring sustainability in both agricultural and industrial development. High priority should go to the standardization and application of such measurement tools. The development of mutually reinforcing packages of technologies, services, delivery systems and public policies can help to prevent the increased release of greenhouse gases.

6.3.3. There is an urgent need to improve our understanding of monsoonal rains in the tropics. In this context, the development of mathematical models for diagnostic tests is strongly recommended. Such models could be used to test model sensitivity to (a) sea surface temperature, (b) coastal upwelling, (c) the impact of afforestation on rainfall and (d) fluctuations in the earth-atmosphere radiation balance as a consequence of increasing greenhouse gases. Model performance depends critically on accurate knowledge of clouds and their distribution in space and time. For this purpose, the use of space technology, especially for preparing cloud climatology with data on outgoing long wave radiation (OLR) is recommended. Model-oriented research needs a firm data base. We recommend, as a matter of very high priority, the preparation of a comprehensive publication on all available data on rainfall. This publication could be made available to all research workers at subsidized prices.

6.3.4. Among the measures needed for limiting the accumulation of greenhouse gases in the atmosphere the following deserve priority attention in research and training:

(1) Improving energy use efficiency.

(2) Promoting the widespread use of renewable energy such as solar energy and biofuels.

(3) Preventing deforestation and promoting extensive afforestation.

(4) Improving water and fertilizer use efficiency.

(5) Improving the monitoring mechanisms for assessing the relative role of the different greenhouse gases in raising the atmospheric temperature.

(6) Intensification of research on the development of environment friendly technologies so as ultimately to eliminate the use of CFCs.

6.3.5. Research and development efforts for adaptation to new situations in temperature, precipitation and ocean levels should include the following:

(1) Population stabilization policies which will ensure that a harmonious balance can exist between the human population and the basic life support systems of land, water, flora, fauna and the atmosphere.

(2) Lifestyle policies which will curb the trend for the wasteful use of energy and consumer goods and which will promote the growth of a conservation society based on the appropriate integration of traditional and frontier technologies.

(3) Reproduction systems of crops appear to be relatively more sensitive to temperature rise and droughts. There is need for screening available genetic variability in crops for identifying donors of genes for tolerance to different abiotic and biotic stresses. The opportunities opened up by genetic engineering for moving genes across sexual barriers has enhanced the value of wild species in crop improvement. There is therefore urgent need for the conservation and efficient utilization of biological diversity.

(4) There is need to improve models to predict and project regional effects relevant to agriculture and aquaculture.

(5) Multi-disciplinary research on abiotic stresses arising from changes in temperature and water stress needs intensification particularly in major crops like wheat, rice and maize, which determine the stability of food security system.

(6) Computer simulation models should be utilized for research on contingency plans and alternative land use strategies to suit different weather probabilities.

(7) Research on the sources of methane build-up in the atmosphere in order to initiate appropriate remedial measures needs support.

(8) Anticipatory research for introducing new coping mechanisms to meet the problems caused by a rise in ocean levels needs to be initiated. Such research should include attention to coastal defense and coastal adaptation techniques, aquaculture technologies and the more extensive cultivation of floating/deep water rice and other plants which have the ability to survive under such conditions.

(9) Collaborative research networks between developed and developing country institutions should be structured in a manner that relevant technologies are developed and disseminated speedily in developing countries.

6.3.6. From the foregoing, it will be obvious that the economic and ecological effect of global warming may vary from country to country. Consequently responses will have to be tailored to specific needs and situations. An inventory of well assessed traditional coping mechanisms (practices) against climatic uncertainties/extreme events (drought/flood, etc) should be prepared for different regions. This could supplement options generated through formal R&D, to meet the situations generated by potential climatic changes.

7. CONCLUSIONS

7.1. We, therefore, recommend that a National Climate Monitoring, Research and Management Board be established in countries where such an organization does not already exist, for developing and implementing in a coordinated manner research and development strategies which can help the country to adapt to emerging situations as well as to contribute to the prevention of impending catastrophes. Such a multi-disciplinary board involving all the concerned agencies of government and appropriate representatives of industry, agriculture, academia, non-governmental organizations and mass media could report to a Cabinet Committee on Sustainable Development chaired by the Chief Executive of the country. Such a Board could monitor on a continual basis the state of the atmosphere.

7.2. Where regional organizations exist such as SAARC and ASEAN in south and south-east Asia, it would be useful to set up a Regional Climate Monitoring and Management Boards comprising the Chairpersons of the National Boards.

7.3. Finally, we wish to emphasize that all the measures recommended by us are essential for promoting sustainable development, irrespective of the extent and type of global warming. Therefore, no further time should be lost in initiating action, although debates on the qualitative and quantitative dimensions of global warming and climate change will always continue among professionals.

Senator GORE. Thank you very much.

Thank you very much, Dr. Woodwell. We will pursue these subjects you raised in questions.

Our second witness is Dr. V. Ramanathan, Professor of Geophysical Sciences at the University of Chicago, who recently published a very important paper on the role of clouds in global warming.

I might just interject for those who are following this hearing a note on the structure of this panel. The first panel talked about the basic models. This panel is talking about feedback loops, possible mechanisms by which the basic action of global warming could be dramatically accelerated or increased or slowed down.

We heard about the increased respiration rate of the earth with the possibility that warming could magnify the release of CO_2. Dr. Cicerone will talk about the special role of methane in a moment.

The other big area of uncertainty has been the role of the clouds. Dr. Ramanathan has done ground breaking work—probably a bad metaphor to use—has done the best work in this area. So, please proceed.

STATEMENT OF V. RAMANATHAN, DEPARTMENT OF GEOPHYSICAL SCIENCES, UNIVERSITY OF CHICAGO, CHICAGO, IL

Dr. RAMANATHAN. Thank you very much, Senator. I am honored to be testifying on this important topic.

As you mentioned, I will comment on the role of clouds in the global warming. As Dr. Schneider mentioned in the earlier testimony, the role of clouds is one of the largest sources of uncertainty in our prediction of the future. So, let us start with some of the things we know very well.

A global warming will be accompanied by increased evaporation of vapor from the ocean which in turn can alter the distribution of clouds around the world.

Such changes in cloud patterns can feed back on the climate and influence the environment in many ways because clouds cycle water through the air, they remove soluble chemicals such as sulfuric acid and cleanse the air, they release enormous heat energy to drive the atmospheric winds, they decrease the ultraviolet radiation at the surface, and above all, the issue I am going to take up, they modulate the radiative heating of the planet in substantial ways. Hence, changes in clouds can significantly impact climate in as yet unpredictable ways. We are at the very early stages of understanding these phenomena.

I am pleased to report that a recent NASA satellite experiment has provided urgently needed insights into the cloud-climate problem and has improved our prospects for resolving the role of clouds in climate change.

This data has yielded a global perspective of how clouds modulate the heat budget of the planet. In my testimony I have included some color images to indicate this global perspective. If I can have the first slide, please.

Clouds have two competing effects on climate. First is the greenhouse effect. Like the gases in the atmosphere, clouds trap the heat radiation and enhance the atmospheric greenhouse effect.

The figure indicates the magnitude of the heat energy trapped by clouds. As we see from the red regions, the largest effect is found over the extensive upper level clouds prevalent in the tropical oceans and in the mid latitude oceans frequented by storms and cyclones. Globally the greenhouse effect of clouds, as you see from that figure, is greater than the effect which would result from a factor of more than 100 increase in the carbon dioxide concentration.

I note for your attention that the cloud effect is particularly large over the warm waters of the equatorial western Pacific Ocean. This feature has important implications for the global warming issue.

For example, it suggests that the trace gas induced warming of the ocean can lead to more extensive coverage of this heat trapping clouds has been pointed out by one of the models. If I am not mistaken, it is probably Dr. Hansen's model which sort of suggested that.

But, these clouds also reflect an enormous amount of sunlight which I call the shading effect, if I can have the next slide, please.

The shading of the ground from sunlight by an overhead cloud is an experience shared by all of us. What this experiment does is is to quantify that effect and the white regions are where the reflection of sunlight is largest by clouds. The largest effect is due to the bright, low-lying stratus and storm track cloud systems over the mid latitude oceans and also due to the upper level cloud systems in the tropical regions. You will see the band of white region there.

The question, then, that the satellite data attempted to answer was (because of these competing effects): do clouds heat or cool the planet? The data, when averaged globally, revealed that the shading effect is larger than the greenhouse effect by as much as 50 percent. Hence, clouds have a global cooling effect.

Now, what is the implication of the issue at hand? We want to be very careful and point out that the fact that clouds have a cooling effect on the present-day climate does not necessarily imply that clouds will offset the greenhouse warming.

Let me give you an example. You see that the strong track cloud systems in the mid latitude ocean is reflecting an enormous amount of sunlight. So, for example, if the system of strong track and the low-lying cloud systems retreat poleward with the warming, you lose the cooling effect of these clouds, which in turn could amplify the warming. It is too soon to predict from our satellite data whether clouds will amplify or ameliorate the global warming.

I want to end my summary of these recent results by commenting on the implication of this data for the recent climate changes.

A major implication of this data is that clouds will have a substantial influence on regional climate changes.

Let me give you an example again. Let us consider the midwest United States. Both during spring and summer clouds significantly reduce the sunlight which otherwise would have heated the soil. So, if the trace gas warming leads to a reduction or even disappearance of this cooling cloud system (as has been suggested by one of the models), the sun's energy absorbed by this region will increase by as much as 25 to 50 watts per meter squared.

What is the significance of this heating? It is nearly a factor of 10 to 20, larger than the direct heat trapping effect of the trace gases.

It is my own view that it is such strong localized feedbacks which can cause major climate surprises, if there are going to be any.

With that, I will conclude.

[The statement follows:]

STATEMENT OF V. RAMANATHAN, PROFESSOR, DEPT. OF GEOPHYSICAL SCIENCES, UNIV. OF CHICAGO

Global Warming and Clouds:

A global warming will be accompanied by increased evaporation of vapor from the oceans which can alter the distribution of clouds around the world. Such changes in cloud patterns can feedback on the climate and influence the environment in many ways because of the following important role of clouds :

Clouds cycle water through the air, oceans and land
remove soluble chemicals such as sulphuric acid and cleanse the air,
release enormous heat energy to generate winds,
decrease the UV radiation at the surface,
and above all modulate the radiative heating of the planet.

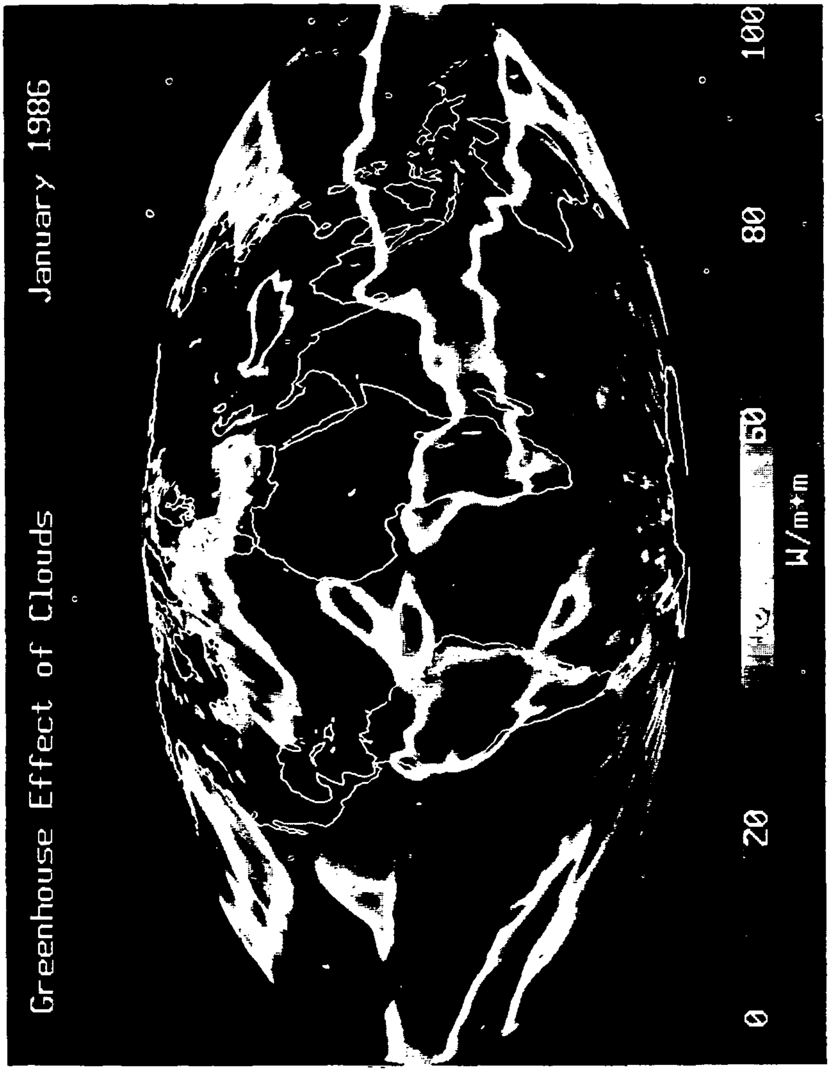
Hence changes in clouds can significantly impact climate, in as yet, unpredictable ways. In particular, regional shifts such as : decrease in the frequency of rain-producing clouds can cause drought and increased pollution; deepening of clouds in the tropical regions can produce more rainfall; poleward shifts in the stormtrack clouds in mid-latitudes can increase the solar heating of the soil and accelerate the soil drying. We are at the very early stages of understanding these phenomenon.

A Recent NASA Satellite Experiment: Major Findings

A three-satellite NASA experiment, the Earth Radiation Budget Experiment (ERBE), was launched from the space shuttle in 1984. The satellites are still gathering data and are processed at the NASA Langley research center. The data provided urgently needed insights into the cloud-climate problem and improved our prospects for resolving the role of clouds in climate change (See articles in Jan-89 issue of *Science* and May-89 issue of *Physics Today*).

We now have a global perspective of how clouds modulate the heat budget of the planet(See the attached figures). Clouds have two competing effects on climate:

<u>Greenhouse Effect of Clouds(</u> See Figure 1): Like the gases in the atmosphere, clouds trap the heat radiation and enhance the atmospheric greenhouse effect. However, unlike the effect of gases which is


Greenhouse Effect of Clouds
January 1986
0
20
60
80
100
W/m*m

distributed uniformly over the globe, the cloud greenhouse effect is concentrated over specific regions of the globe. The largest effect (the red regions) is found over the extensive upper level clouds(Cirrus) prevalent in the tropical oceans and in the mid-latitude oceans frequented by storms and cyclones. When the data shown in the figure is averaged over the globe, clouds are found to trap about 30 W. m^{-2}. This greenhouse effect of clouds is greater than the effect which would result from a factor of 100 increase in the CO_2 concentration of the atmosphere.

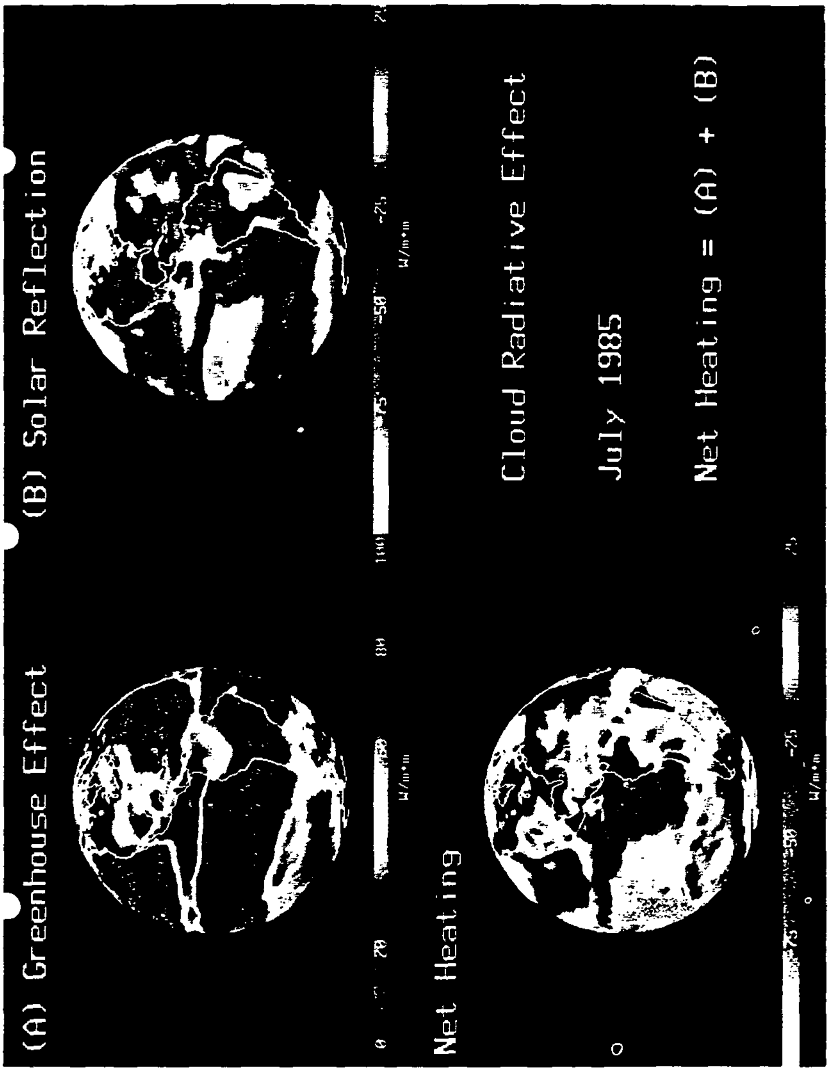
The cloud effect is particularly large over the warm waters of the equatorial western pacific oceans. This feature has important implications to the global warming issue. It suggests that, the trace gas induced warming of the ocean can lead to more extensive coverage of the heat trapping clouds . But these clouds also reflect enormous amount of sunlight, as revealed by the satellite data(See Fig.2).

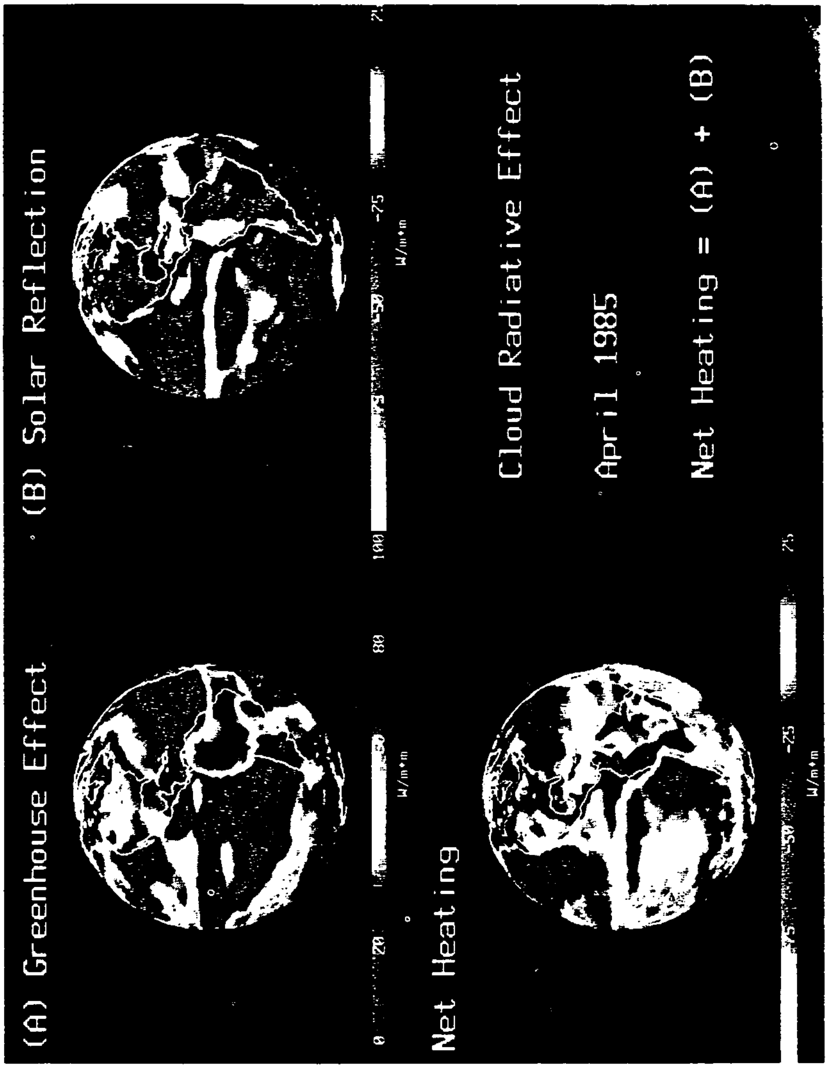
Shading Effect of Clouds: (**See Figure 2**): Clouds also reflect sunlight. The shading of the ground from sunlight by an overhead cloud is an experience shared by all of us. The largest effect is due to the bright stratus and storm track cloud systems over mid- latitude oceans and due to the upper level cloud systems in the tropical oceans.

Do Clouds Heat or Cool the Planet ?. Thus, while the greenhouse effect of clouds tend to warm the planet, the shading effect tends to cool it. The net effect(Fig. 2) when averaged globally reveals that the shading effect is larger than the greenhouse effect by about 50 %. *Hence clouds have a global cooling effect* . This cooling effect is particularly large over the mid to polar atlantic and pacific oceans. Since the planet must maintain global energy balance, the cooling effect by clouds is approximately balanced by a corresponding heating effect under cloudless skies.

Implications to the Global Warming Issue: The fact that clouds have a cooling effect on the present day climate *does not necessarily imply that clouds will offset the greenhouse warming by the trace gases.* For example, if the system of storm-track and stratus cloud systems(which produce a strong cooling of the mid latitude oceans)retreat polewards with a warming, the absence of the cooling effect can significantly amplify the mid-latitude warming. *It is too soon to predict from the satellite data whether clouds will amplify or ameliorate the global warming.* However, the magnitude of the cloud effects revealed by the data

99-447 0 - 89 - 4


(A) Greenhouse Effect
(B) Solar Reflection
Net Heating
Cloud Radiative Effect
July 1985
Net Heating = (A) + (B)


(A) Greenhouse Effect
(B) Solar Reflection
0
20
80
100
W/m*m
-75
-50
-25
25
Net Heating
Cloud Radiative Effect
April 1985
Net Heating = (A) + (B)

are such that changes of about a few percent in their effects are sufficient to significantly alter the trace gas effects.

Implications to Regional Climate changes: A major implication of the stellite data is that, clouds will have a substantial influence on regional climate changes. For example, consider the midwest united states in Figs. 2 & 3. Both during spring and summer, clouds have a large net cooling effect on this region. If the trace gas warming leads to a reduction or even disappearance of these cooling cloud systems(as suggested by some models), the solar energy absorbed by this region will increase by as much as 25 to 50 W. m^{-2} over the midwest(according to Figs. 2 & 3). This increase in the solar energy is larger than the heat trapped by the trace gases by a factor of about 10 to 20 !. The increased solar heating can also lead to drying of the soil. This sort of localised and strong positive feedbacks are possible because of the coupling between the atmospheric circulation, cloud-radiative heating , surface temperature and soil hydrology.

Prospects for the Future:

Validation of Global Models: The satellite data from ERBE can be used directly to validate the treatment of cloud in climate models. Several groups have already begun the process of model verification. Examples of the ongoing studies are : National Center of Atmospheric Research(Dr. J. T. Kiehl) ; Geophysical fluid dynamics laboratory(Drs. Manabe and Wetherald); Oregon State University(Dr. Schelesinger); and Intercomparison of several climate models(Dr. R.D. Cess, SUNY stony Brook). By comparing the data with their models, these groups should be able to identify modeling deficiencies and suggest ways to improve simulations of clouds and climate.

Cloud-Climate Interactions during observed Climate Changes: Major climate shifts such as the 1988 summer drought in the U. S or the world wide changes following the El-nino of 1983, should have produced significant regional changes in the heating or cooling effects of clouds. Analyses of the cloud effects from the ERBE data should give clues regarding how clouds respond to climate changes.

<u>**Need for future Space Observations of the Radiation Budget:**</u> The ERBE data will not continue after the early 1990's. It is of great importance to continue accurate and calibrated measurements such as ERBE to enable the understanding and prediction of how trace gases and clouds influence the climate. In addition , long term(alteast 20 years) monitoring of the cloud effects on the radiative heating of the Earth is the only promising way available to us to determine whether clouds will amplify or ameliorate regional climate changes (induced by a global warming). Of-course such data gathering will yield the desired knowledge only if they are accompanied by field observations and realistic global models.

<u>**Need for More Detailed Global Models:**</u> The ERBE data clearly revealed that the major radiative heating and cooling effects are caused by cloud systems whose sizes are much smaller than the spatial dimensions included in our current models. The models , due to lack of adequate computing resources, resort to several short cuts such as treating the entire U. S. A by fewer than 30 points. The ERBE data suggest that the models have to increase the number of points atleast four fold, to mimic the observed cloud effects. We need a significant improvement in the computational power made available to the modeling groups to accelerate progress.

Acknowledgements:

The ERBE work reported here is a collaborative effort between DR. R. D. Cess of SUNY, Stony Brook; Drs. B. R. Barkstrom and E. Harrison of NASA Langley and the author's group at the University of Chicago.

APPENDIX: BACKGROUND ON CLOUDS

I. Fundamental role of these spectacular objects in the sky

Water enters the atmosphere from the surface in the form of vapor (gas), travels upwards, and falls back down on the surface in the form of rainfall or snowfall. The change from vapor to rain or snow happens inside clouds. Hence, *clouds play a fundamental* role in *cycling water between the oceans, the atmosphere and the continents.*

II. What phenomenon enables us to see clouds?

Clouds consist of tiny particles of water drops (less than 0.01 centimeter or .01 in in size) or ice crystals which scatter significantly all visible wavelengths of sunlight while the air scatters preferentially blue wavelengths. Hence *clouds appear white in the blue sky.*

III. How thick are clouds and when do they precipitate?

Clouds that are seen with our eye range in thickness from meters (5 to 10 feet) for thin stratus to as thick as 10 kilometers (6 miles), for cumulonimbus clouds seen in tropical storms. When the thickness exceeds a few kilometers (a mile), the drops and crystals grow rapidly (in 15 minutes) and become too large and heavy to stay in the air. Hence *thicker clouds precipitate as rain or snow.* The shallow or thinner clouds, on the other hand, stay in the air until they evaporate back into vapor.

IV. Processors of chemicals in the air:

Chemicals such as sulphuric and nitric acid dissolve in cloud drops and are removed when the drops fall off. The non-precipitating clouds, on the other hand, have a strong effect on the air chemistry since they remain in the atmosphere for hours and significantly scatter sunlight which drives the photo-chemistry. Lastly, turbulent motions within clouds transport gases vertically. Thus clouds *play an important role in procesing numerous chemicals in the air.*

V.Modulators of Ultra- Violet radiation reaching the ground:

Clouds reflect about 25 to 80 % of the incident UV light back to space . Hence, next to Ozone, *clouds have a dominant influence on the UV light reaching the ground.*

VI. Generators of atmospheric winds :

Solar energy is used to evaporate water from the surface. The vapor stores this energy and this latent energy is released when the vapor condenses in the atmosphere. *This latent heating in clouds drives the large scale equator to pole winds, the jet streams and the destructive winds in tropical storms.*

Senator GORE. Thank you very much.

Our last witness on this panel is Dr. Ralph Cicerone, head of the Atmospheric Gas Measurements Section of the National Center for Atmospheric Research, and he will discuss the role of methane in global warming. Welcome.

STATEMENT OF RALPH J. CICERONE, DIRECTOR, ATMOSPHERIC CHEMISTRY DIVISION, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, BOULDER, CO

Dr. CICERONE. Thank you, Senator.

Mr. Chairman and Senators, thank you for the opportunity to be here today.

In the time that you have given me, I am going to focus on atmospheric methane because it is the second most important greenhouse gas, and it is the case, I think, that we have not given enough attention to some of the other greenhouse gases that are important along with carbon dioxide.

In the time, then, I will outline some of the evidence that shows that methane is increasing, some of the factors involved, and then focus on the future, what kinds of feedbacks and surprises we might expect—or at least we have to look out for.

First, reliable measurements have shown now that atmospheric methane is increasing its concentration worldwide at a rate of about 1 percent per year. The modern data set began around 1978. But, before that time we also have some strong data from the year 1951 that show that there was about 30 or 35 percent less methane in the atmosphere in 1951 than there is now, and prior to that—actually more recently discovered through this elegant ice core work that Dallas Peck mentioned—there is strong evidence that the pre-industrial concentrations of methane were less than half of that of today.

So, indeed, atmospheric methane has more than doubled in the last 100 years as shown by the ice core data. And from even older ice cores still we now have very interesting evidence that during ice ages, methane concentrations were about ⅓ of a part per million. Now, the number today is 5/3, five times higher.

During the warmer periods between the last two ice ages, methane concentrations were about ⅔ of a part per million, so that is about equal to the pre-industrial level, less than half of what we have today.

In the 1980s this annual increase of 1 percent per year adds up to 50 million extra tons of methane in the atmosphere globally each year.

Now, we understand some of the factors behind this increase so that we can give you a hand waving explanation of why this is occurring, but I am afraid we do not understand them well enough to predict whether this same kind of rate of increase is going to be maintained or become larger or even slow down a little.

Let me talk for a couple of minutes about the sources and sinks of atmospheric methane. I have actually given you a detailed table on page 4 of my testimony which I will not go into, and with your permission, I attach a lengthy appendix which adds a lot of substantiation and detail to the entire testimony.

Senator GORE. We will include that in the record by reference.

Dr. CICERONE. Thank you.

In any case, this table is my best shot based on all kinds of reasoning as to where the methane is coming from. The numbers there are expressed in millions of metric tons per year, a trillion grams is a million metric tons.

For several of the sources that I indicate here, I am afraid that—you can count the number of measurements on which the estimates are based on one hand and still have some fingers to spare. So, I am saying that this table is my best shot, but I am also saying there has not been very much work done in some of these cases.

But the three largest methane sources now appear to be two agricultural activities and one natural process. The two agricultural activities are rice growing and the domestication of animals, mostly cows and sheep. The third environment that gives rise to a lot of methane from what we can tell are natural wetlands of all kinds including all kinds of bogs, tundra, and so forth.

There are at least two other methane sources that are growing faster, however, than the major ones, and those are losses of methane from natural gas exploration, transmission, and usage, and also losses due to coal mining and coal handling.

The present sources are not very quantified yet, but we can tell by our usage and consumption rates that the rates of growth are large.

Now, once in the atmosphere, methane is destroyed by several natural processes that limit the average survival time of a methane molecule to about eight or ten years, similar to that of carbon dioxide, actually.

The dominant destruction process for methane is an atmospheric chemical process that involves an hydroxyl radical, a fragment of a water molecule that is formed in a sunlit atmosphere which can pluck the methane molecule apart, and that is irreversible.

Well, so what? What are the effects of increasing methane?

One of the largest—probably the largest global impact of increasing atmospheric methane is the acceleration of the otherwise natural greenhouse effect.

As I said earlier, methane is the second most important gas. I can give you an example of that. If you simply compare the changes in carbon dioxide and methane that have occurred in the last 100 years, carbon dioxide going from about 275 or 280 parts per million to 350 now and methane going from about ⅔ of a part per million to 5/3 of a part per million where it is now, the radiative forcing—that is this infrared forcing part of the climate energy budget—the methane effect is about 40–45 percent as large as carbon dioxide itself. So, that is something that we should be watching out for, and it is nontrivial.

Looking into the future, what kinds of feedbacks can we anticipate, and we should be watching for? What kinds of surprises might be built into the system?

I should say that in many scientific questions, a scientist has to scratch his or her head a lot to be able to appreciate the connections and feedbacks between a variable that is changing and how it might affect the change in another variable.

When one looks at the atmospheric methane and global carbon cycle question, the feedbacks standout, and you do not have to scratch your head very hard. They are there, at least in principle.

For example, there is one that is an atmospheric chemistry effect, and that is that increases of atmospheric methane and also carbon monoxide, should they occur, can actually decrease the atmosphere's ability to consume the methane through this hydroxyl radical attack that I mentioned.

The atmospheric chemistry destruction of methane actually proceeds in two pathways, however. In one of those pathways we get this feedback where the atmosphere's ability to consume methane is suppressed and a little bit of ozone is also consumed in the process in the lower atmosphere.

But in the other pathway there should not be any change at all in the atmosphere's ability to consume methane which would mean that the future increases of methane should just depend on the sources rather than having this feedback. But in the process some ozone, another greenhouse gas, is produced in the lower atmosphere. And which path is being followed depends on some details that I have mentioned in the Appendix to my testimony.

Whatever the case, it is fairly certain that methane is going to continue to build up globally because so many of the identified sources that we know about are increasing due to human activities.

So, along with the other greenhouse gas increases, we all expect some climatic warming to occur. Now, these can affect methane sources and probably will.

Methane-producing microbial organisms work faster as temperature increases. So, as a region's soils warm up in the future, more methane should be released, for example, from northern wetlands and temperate zone rice paddies. This will be true as long as there is adequate organic matter, water, and other nutrients.

Northern wetlands and tundra look to be especially important because there is so much organic material there that can be converted to methane.

So, if these areas become warmer and stay as wet or wetter than they are now, there will be as much moisture available and increased time between the spring thaw and fall freeze up, we then expect more methane to be released. In fact, a lot more.

But, if these areas get warmer and drier, then there should actually be less methane released but more carbon dioxide. That is the way the decomposition processes work.

Now, a potentially more explosive type of feedback is represented by something that we call methane hydrate deposits. These are large but not particularly well quantified layers of solid methane and water structures that exist under some permafrost areas and in some oceanic sediments along margins of continents, mostly. These structures are stabilized by cold surroundings and overlying pressure, so that they are intact as long as nothing changes in their environment.

But one projected effect of a climatic warming is that some of these methane hydrate deposits can break apart releasing gaseous methane, possibly even explosively. Based on a few indicators, we guess that this may be already occurring at a small rate, but the real concern is over future possibilities especially in shallow ocean areas that might be sensitive to global warming. And I gave a few examples of those places in my written testimony.

We cannot quantify this phenomenon well at all yet, but if it occurs, it can only add methane to the atmosphere, and it certainly would not work as a stabilizing feedback.

In closing I should say that these feedback processes have really yet to be studied seriously, and there are probably many others that have yet to be identified.

They could turn out to be quite dramatic or perhaps not as important as our present guesses indicate.

But I can close by saying that none of these processes have been included to date in climate models, and I think the same statement is largely true for the entire carbon dioxide issue and also that of another greenhouse gas, nitrous oxide.

Thank you, Mr. Chairman.

[The statement follows:]

STATEMENT OF DR. RALPH J. CICERONE, DIRECTOR, ATMOSPHERIC CHEMISTRY DIVISION
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Mr. Chairman and Senators: Thank you for the opportunity to be here today. In the time that you have given me I will describe how atmospheric methane is growing in concentration in the global atmosphere, why it is important and the factors that are involved in this increase. I will also try to outline some of the ways that the growing greenhouse effect will feed back on, and alter the rate of increase of methane. With your permission, I will include one Appendix to my statement; the Appendix provides more detail, references and substantiation for my testimony.

Atmospheric Methane Is Increasing

Reliable measurements show that atmospheric methane (CH_4) is increasing in concentration worldwide at a rate of 1% per year. In the Northern Hemisphere its concentration is about 1.7 parts per million (ppm), while south of the equator it is about 1.6 ppm. The contemporary data set began in 1978; because of the strength of the measurement technique and the number of independent laboratories around the world that agree, this trend is firmly established. Separately, other solid experimental evidence has shown that in 1951 there was 30 to 35% less methane in the atmosphere than now. Further, very elegant experiments have been performed on old ice cores whose ages are known. By extracting the air from these cores, scientists have shown convincingly that methane has increased from about 0.65 ppm a century ago. Even older ice cores have now been analyzed. During the last 160,000 years, two Ice Ages have occurred. In each of the coldest epochs, methane concentrations fell to about 0.3 ppm, while in warmer interglacial times they were 0.6 or 0.7 ppm, never higher. So now we know that carbon dioxide and methane concentrations moved together—high when Earth was warm, low when cold, but at all times these two greenhouse gases have been less abundant than now, at least during the last 160,000 years.

In the 1980's, the annual increase of methane, about 16 parts per billion, adds up to 50 million extra tons of methane in the global atmosphere each year. We have some understanding of why this is happening but not enough to be able to predict whether the rate of increase will become larger or smaller in the future. It is very unlikely that we will ever see the lower concentrations of the pre-industrial era ever again.

Sources and Sinks of Atmospheric Methane

The major sources of atmospheric methane are probably identified now after some years of research. A recent listing of such sources appears in Table 1. The annual worldwide release rates of methane in the table are expressed in trillions of grams per year (10^{12} grams per year). One trillion grams is one million metric tons. The range given for each source is meant to be the likely range but in several cases, the actual source strength could easily lie outside the range that is shown here. While the work of some very good scientists from different countries has gone into this table, the numbers could change as more effort is expended. For several of these methane sources I know that the number of measurements that have been made can be counted on one hand with fingers to spare. We can and must determine the methane sources and their sizes more reliably. Similarly, while many of these global sources are growing each year, their growth rates are not known as well as we need to know them.

In constructing this list of global methane sources we used information from field measurements of methane emissions, from the isotopes of carbon (^{12}C, ^{13}C and ^{14}C) in the methane, from constraints placed on the total of all methane sources by data on methane distributions and on the behavior of similar chemicals, and from results of mathematical models of atmospheric chemical reactions and air motions. My approach was to employ all relevant and complementary information even though the data are fragmentary and preliminary in some cases.

At present the largest methane sources are probably the two agricultural activities—rice agriculture, release by ruminant animals (cows, sheep, goats)—and natural wetlands of all kinds. These environments (rich waterlogged paddy soils, cow guts and wet organic-rich

TABLE 1. Annual Methane Release Rates for Identified Sources with Likely Range for Each. (from Appendix).

Identity	Annual Release 10^{12} g CH_4	Range, 10^{12} g CH_4
Enteric fermentation (animals)	80	65–100
Natural wetlands (forested and nonforested bogs, forested and nonforested swamps, tundra and alluvial formations)	115	100–200
Rice paddies	110	60–170
Biomass burning	55	50–100
Termites	40	10–100
Landfills	40	30–70
Oceans	10	5–20
Freshwaters	5	1–25
Methane hydrate destabilization	5?	0–100 (future)
Coal mining	35	25–45
Gas drilling, venting, transmission	45	25–50
Total	540	400–640

This candidate list obeys the constraints derived in the Appendix, but it will be revised as stronger constraints develop.

natural soils) provide what is needed for methane-producing microbes: organic material, moisture,warmth and absence of oxygen.

Several other methane sources are growing even faster than those due to human rice agriculture and cattle production—losses from natural gas exploration and transmission lines and in coal mining. These sources are not very well quantified yet. The possibility that methane is already escaping from large gas-hydrate deposits, and that the escape rate will increase dramatically with global warming, is real but hard to evaluate with existing data.

Once in the atmosphere, methane is destroyed by several natural processes. The average survival time for a CH_4 molecule is about ten years, perhaps eight years. The dominant process that determines this survival time (by destroying methane) is a chemical reaction that occurs in the sunlit atmosphere: hydroxyl radicals (OH) pull methane apart. This occurs mostly (85%) in the lower atmosphere but also in the stratosphere, where other processes also destroy methane. These hydroxyl radicals are fragments of water-vapor molecules. Ultraviolet sunlight, ozone and moisture make hydroxyl radicals at rates which are presently not directly measurable but can be estimated roughly. A second natural process that destroys methane is the consumption by certain soil microbes; air containing methane can move into upper soil layers where bugs with the right capabilities remove methane from it. This latter process is extremely interesting but is probably much less effective than the atmospheric chemical reaction with hydroxyl radicals. None of the methane sinks are understood at all well enough to know how steady and reliable they are. Indeed, there are solid ideas about how human activities can decrease the effectiveness of natural methane sinks.

Effects of Increasing Methane

One global impact of increasing atmospheric methane is the significant acceleration of the forcing of the greenhouse effect. Methane is the second most important gas that is changing the energy budget (and hence the climate of Earth). If we compare the energy changes due to increasing carbon dioxide from 275 ppm (its concentration 100 years ago) to 350 ppm (its concentration now) to that due to increasing methane from 0.7 ppm (its concentration 100 years ago) to 1.7 ppm (its concentration now), we find that the forcing due to methane is 45% as large as that of carbon dioxide. The relative contributions of CO_2 and CH_4 in the future will depend on how each gas grows in concentration, but methane will probably continue to represent a significant force. Each added methane molecule is as potent as about 40 carbon dioxide molecules.

Methane also is a central player in the chemistry of the atmosphere. In the lower atmosphere (troposphere) methane, through its chemical reactions, exerts control over how much hydroxyl is present. In this way, methane consumption actually depends on methane amounts; a runaway type of feedback is possible. Also in the troposphere, methane amounts influence the rates of production of ozone, which is a greenhouse gas itself (and is an undesirable pollutant in the troposphere). In the stratospheric ozone layer, methane is also important chemically. It slows the rate of destruction of ozone by chlorine in one part of the stratosphere, but it enhances the destruction at higher altitudes when hydrogen oxides form through methane's decomposition. Overall, the spatial patterns of ozone destruction are being influenced strongly by methane. Several other environmental roles of atmospheric methane are mentioned in the Appendix to my statement.

Feedbacks, Surprises and the Future

In many scientific issues, one has to scratch his or her head before he or she can begin to appreciate that there may be connections between the variables, connections that can allow one change to affect the size or direction of another change. With atmospheric methane and the global carbon cycle it is the opposite—several feedbacks stand out and are strong in principle. One of these was identified in 1976 when two scientific groups explored whether increases of atmospheric methane and carbon monoxide (CO) could decrease the hydroxyl amounts in the troposphere, thus leading to faster rates of buildup of methane and CO. These ideas looked good hypothetically but at that time there was no evidence that methane was increasing. Indeed, all of the scientists who thought of this were surprised to learn years later that methane is increasing at 1% per year.

This atmospheric methane feedback actually has two possible pathways. In one, methane increases lead to hydroxyl decreases which, in turn, cause methane to increase further, and a small decrease in tropospheric ozone. In the other, methane increases lead to increased production of hydroxyl and of ozone. Which path is being followed now and in the future depends on the distribution of nitrogen oxide gases in the troposphere (which is poorly known now), and on future emissions of nitrogen oxides from mobile and stationary sources.

It is far more certain that methane concentrations in the global atmosphere will continue to increase because so many sources are increasing due to human needs and activities. Along with the other greenhouse gas increases, this should imply some climatic warming. Methane-producing microbial organisms work faster as temperature increases, so as a region's soils warm in the future, more methane should be released, for example from northern wetlands and temperate-zone rice paddies. This will be true as long as there is adequate organic matter, water and other nutrients. On the other hand, methane production from landfills should not be as sensitive to surface temperatures. Northern wetlands and tundra look to be especially important. There is so much organic material there that a very large potential exists for methane release. If these areas become warmer and there is moisture available for more days each year (increased time between spring thaw and fall freezeup) we expect more methane to be released. But if these areas get warmer and drier, there could be less methane released but more carbon dioxide.

A potentially more explosive type of amplifying feedback is represented by methane-hydrate deposits. These are large but not well quantified layers of solid methane and water structures that exist under some permafrost areas and in oceanic sediment along margins of continents. Pressure and cold surroundings keep them intact so a climatic warming could cause some of them to break apart, releasing gaseous methane. Based on a few indicators, we can guess that this may already be occurring at a small rate but the real concern is over future possibilities such as shallow ocean areas that would be sensitive to global warming, e.g., Beaufort Sea of Canada, regions off Siberia and others. At present, this possible phenomenon has not been quantified at all well, but if it occurs, it will add methane to the atmosphere, not subtract it.

A further possibility concerns the functioning of processes that consume methane in soils and in various water bodies. These processes are limiting the release rates of methane from various sources such as rice paddies, lakes and landfills and in some soils they actually consume methane from the air. There are some field measurements that show that as forests and grasslands are converted to agricultural lands, the capability of the soils to consume methane is decreased. It is too early to say if this matters globally, but it is clear that we take for granted the functioning of biological methane sinks without knowing how they work. Maybe they will slow down or even speed up.

In closing I should say that these feedback processes have yet to be studied seriously (and others are yet to be identified). They could turn out to be more dramatic or less important than our present guesses indicate. None of them have been included to date in climate models. The same statement holds for the other greenhouse gases such as carbon dioxide and nitrous oxide. Progress in research is being held back now by several factors, all of which are frustrating and are much more institutional than scientific in character. The field of atmospheric chemistry and biogeochemistry is new and very small, so experts are few and there are no established advocates in funding agencies. There is a large perceived need to keep other more conventional fields going where the problems for research are more time-honored, and there are other areas of research that have usually been perceived to need quicker attention, e.g. localized pollution problems. These other areas get the research budgets, staff and equipment in most institutions.

Senator GORE. Thank you very much. I want to express my thanks to all three of you again, and we will have five minutes of questions for the panel.

About 15 years ago scientists came up with a model that was used to predict the loss of stratospheric ozone as a result of a particular group of chemicals known as chlorofluorocarbons released into the atmosphere. Their model predicted a certain rate of loss.

The model did not include a chemical process which we now know takes place over Antarctica. Very high polar stratospheric clouds provided ice crystals on the surface of which the reaction between chlorofluorocarbons and ozone took place much more rapidly than predicted in the model.

The colder the temperature the more the reaction speeded up, magnifying the amount of ozone depletion and leading to the sudden shocking emergence of a continent-sized hole in the ozone layer.

Now, the models 15 years ago were described by policy makers as uncertain and perhaps not sound enough to serve as the basis for changes or policy changes. Indeed, the models were wrong. They predicted damage much less severe than that which has actually occurred.

What you are telling us, the three of you on this panel, is that even though we are relatively comfortable with the scientific consensus about global warming, there are several potential magnifiers or feedback loops which could make the warming much worse and cause it to occur much more rapidly.

The uncertainty is on both sides of the predictions given us by scientists using their best judgment.

Now, if I could just put this in laymen's language, you are saying, Dr. Woodwell, that the warming itself can change the rate at which carbon dioxide is released by the earth's biosystem into the environment and the rate at which it is reabsorbed. So increasing temperatures could trigger a feedback loop that would speed up the increase in the concentrations of CO_2, correct?

Dr. WOODWELL. That is correct.

Senator GORE. Now, Dr. Ramanathan, what you are saying is the models on which everyone relies assume that the warming will cause greater evaporation rates and more moisture in clouds which, in turn, will have a very complicated effect. They will trap more heat. They will also reflect more of the sun's incoming radiation, back into space.

And you are telling us that although this major uncertainty about what clouds will actually do complicates our ability to predict the actual effects of these increased gas concentrations and increased warming. But the cloud system could very easily turn out to be a magnifier and make the problem worse especially over land masses where it could intensify the incidence of drought, is that correct?

Dr. RAMANATHAN. Yes, absolutely.

Senator GORE. Now, Dr. Cicerone, you are saying that we have paid too little attention to the role of methane as a greenhouse gas. Each molecule of methane is far more effective as a greenhouse gas than each molecule of carbon dioxide, correct?

Dr. CICERONE. Yes, perhaps 30 to 40 times more effective.

Senator GORE. 30 to 40 times more effective. Parenthesis: each molecule of chlorofluorocarbons is about 20,000 times more effective. Do I have that right, 10,000 or 20,000, Dr. Woodwell?

Dr. WOODWELL. That is right.

Dr. RAMANATHAN. The chlorofluorocarbons is about tens of thousands more efficient.

Senator GORE. I was looking for whether each mollecule of chlorofluorocarbons was 10 or 20 thousand times more effective?

Dr. RAMANATHAN. Between 10,000 to 20,000. It is difficult to be more precise than that.

Senator GORE. Well, close enough.

Now, each molecule of methane is, as you said, 30 to 40 times as effective as a molecule of CO_2. You outlined for us the sources of methane increases in the atmosphere. But you are also telling us that increased temperatures caused by the initial global warming can trigger further increases in methane giving us another feedback loop that could cause the problem to be much worse and occur much more rapidly.

Specifically, some of the natural wetlands and some of the tundra area and some of the shallow ocean floors that warm as a result of the initial warming could begin to disgorge a methane now trapped in them and magnify the increase of gases that cause the greenhouse effect, correct?

Dr. CICERONE. Yes.

Senator GORE. So, the uncertainty is very much on the downside as well as the upside and just as with the ozone depletion problem, we could see one or more of these feedback loops get out of control. And I might add, there is a possibility that we will discover other gases that play this role. Carbon tetrachloride is a recent addition to the list of greenhouse gases, and we may find some other new and important sources.

Dr. CICERONE. Senator Gore, I would like to comment on the statement you made about the stratospheric ozone issue because I think there were lots of pressures on the scientists—and I was one of them. I testified in these chambers before Senator Bumpers in 1975 on the issue and several other times.

There were lots of pressures on us and on you as human beings or as representatives of industry, or in our own daily lives, to look at the uncertainties and hope that the models in those days were making an error in only one direction.

And I think no one was trying to obfuscate so much as we were all victim to the same kinds of natural pressures to say we hope we are exaggerating the effect.

It turned out with stratospheric ozone we were not. We actually missed the predictions on the wrong side. The damage is worse than we predicted.

For the global picture, it is about the way it was predicted, but for the polar cap regions where the problem is getting worse over Antarctica, we missed it completely.

But I think we have to remind ourselves when we talk about these scientific uncertainties, we can miss on the low side as well. We did miss on the low side with ozone. The kinds of things that Dr. Woodwell talked about this morning give us cause to think that we ought to look at the upper end of the effect, the worst side of it, and put more attention on that to see if we are missing it.

Senator GORE. I would just add in closing that when you say on the global picture you are about right. The testimony we had here indicated that it is happening at least twice as fast, on a global scale.

Dr. CICERONE. I do not argue that. It is just that we missed it by much worse over Antarctica.

Senator GORE. But even globally it is happening at least twice as rapidly. Again, to underscore the central point, we could have a similar surprise that leads us to recognize that by failing to act and moderate these human caused changes, we could trigger a feedback loop that magnifies the results of what we started.

I am sorry to go a minute or so over. Senator Bryan.

Senator BRYAN. Thank you very much, Mr. Chairman.

So, the greenhouse gases you have mentioned are CFC, CO_2 and methane, that are contributing factors to this environmental degradation that we have been talking about this morning. Are those the three principal contributors?

Dr. WOODWELL. Nitrous oxide, yes, plus ozone and a few others.

Senator BRYAN. Could you rank them in order of importance? You have talked to us about in terms of the individual multiplier effect based upon a molecule, but in terms of the total impact would CFCs be more serious, CO_2, methane, nitrous oxide?

Dr. RAMANATHAN. CO_2 is the largest. It is roughly half the damage, if I can call it that, and then I would put CFCs and methane roughly of similar order, but it depends on the year by rate of increase. If you look at the last decade chlorofluorocarbons have a larger effect than methane. If the total effect, let us say, is 100 percent, carbon dioxide would give you roughly 50 percent. Methane and CFCs would be another 35 percent. Another 15 percent is from gases like nitrous oxide and a host of other chemicals, Senators, which we have not even talked about here.

Another issue which is looming on the horizon concerns ozone in the lower atmosphere—not the stratosphere, but the lower atmosphere it is an enormously efficient greenhouse gas, and there are some local observations over Germany and some here that would suggest they are increasing for reasons we have not discussed here.

Senator BRYAN. Let us talk about each one of these gases in the context of how we might have to change our own conduct, our own life-style. How can we change the way in which do business, so to speak, on this planet in order to have the greatest impact on the problem?

Dr. WOODWELL. Well, there is not any question that we can affect the amount of carbon dioxide released from the two sources that I mentioned, fossil fuels and from deforestation. We have an international instrument at the moment that it should have the capacity for eliminating the CFCs and certainly every step should be taken to do that thing.

Senator BRYAN. Are you talking about the Montreal Protocol?

Dr. WOODWELL. Yes, the Montreal Protocol which has recently been reopened and apparently not too successfully. But it should be possible to eliminate further releases, further production of the CFCs and, from my perspective, that is an urgent matter.

The other gases are difficult to control.

Dr. CICERONE. With carbon dioxide, though, the single easiest step would to be increase energy efficiency. I do not think there is any question about that.

For the more distant future, dependence on energy sources other than fossil fuel combustion are things we have to look into.

With CFCs I agree completely with Dr. Woodwell. I note that the Montreal Protocol, the machinery that we have; that is, the instrument that we have internationally to control CFCs hardly recognized the greenhouse effect of CFCs. It was based totally on the ozone layer damage.

So, we have added motivation to implement that agreement and to strengthen it.

With methane I think we are dealing with so many mixed sources right now that we have to look at things like controlling leaks from natural gas and coal mining, different landfill processes, looking at some ways to manipulate cattle and rice agriculture to release less methane, and I am not sure that can be done.

Senator BRYAN. With respect to the Montreal Protocol, a number of the underdeveloped countries, as I understand it, have chosen not to participate. To what extent is their absence from the Protocol going to compound the problem of those countries which are signatories?

Dr. CICERONE. It depends on what kind of production facilities are built there. For example, whether more highly developed countries might have an incentive to build expansive plants in Third World countries and get away with it. I think the production will continue to increase if it is totally unregulated—the chemicals have proven to be useful. There is no question about that. But whether the world has the resolve to truly limit their increased usage is the question.

There are all kinds of ways around the Protocol, I am sure.

Senator BRYAN. Are you satisfied with the time scale that is proposed in the Protocol? Does it need to be accelerated?

Dr. CICERONE. It definitely has to be accelerated. The grounds on which the Protocol were agreed upon in the summer of 1987 preceded the strong evidence from the expedition in the fall of 1987, actually the austral spring and summer showed most of us that there was no escaping the conclusion that CFC has caused the ozone hole.

Before that time many of us had theories, and we expected it, but the evidence was not in yet. So, the Protocol in its present form, which looks weak to us, was perhaps naturally weak because all the evidence was not in yet. Now it looks like it definitely has to be strengthened and accelerated.

Senator BRYAN. Doctor, from a scientific perspective, what would be your recommendations? If you were sitting at the conference table and negotiating, what would you be pushing for?

Dr. CICERONE. In terms of CFCs?

Senator BRYAN. Yes.

Dr. CICERONE. Nearly complete regulation. We know now in principle that adequate substitutes can and have been created for nearly all applications—not yet in commercial quantities—and there are a few glitches here and there about materials and perhaps some extra cost of retrofitting a lot of compressors, but these things can be done compared to the risks we are taking and the limited options that we are going to have with controlling CO_2 and methane, I think we have to get rid of the CFCs.

It is the simplest part of the issue to understand scientifically. We know where they are coming from. We know where they are going to, and with some of these other gases there is a little more uncertainty.

Senator BRYAN. What would your date be for total elimination?

Dr. CICERONE. The goal should be as soon as possible. I do not know what is practical, but I suspect several years is practical.

Senator BRYAN. Thank you very much, Mr. Chairman.

Senator GORE. I might add at that point that I appreciate the Senator from Nevada cosponsoring legislation which I have introduced to eliminate CFCs in the United States entirely within five years.

The Protocol as it now exists calls for a 35 percent reduction by the year 2000. Even that reduction might not be seen if certain loopholes are taken advantage of.

Just to stabilize the rate of damage, we would need an 85 percent reduction, and we should have a 100 percent reduction.

I am pleased to invite to participate the Senator from Colorado, Senator Wirth, with whom I have worked on this larger issue, for five minutes of questions of this panel and invite him to participate in the remainder of the hearing as well.

Senator WIRTH. Thank you, Senator Gore. Thank you very much for including me in this and once again, I want to add my words of commendation to you who have been leading on this effort for so many, many years.

I also want to welcome Dr. Cicerone and Dr. Schneider from the National Center for Atmospheric Research in Boulder, right around the corner from where I live. They have been tutoring me for years on this issue, and I am glad no one has tried to change your testimony on the revelations that you all are coming up with. I hope that those revelations do not cost you all in terms of funding from the National Science Foundation.

Senator Gore, NCAR is heavily funded by the National Science Foundation, and I hope that the Office of Management and Budget does move in and cut their budget because of what they have been saying.

Let me just ask you all, it seems to me that once again you are coming forward with very striking evidence. Are you telling us that the evidence is clear enough—that the evidence is clear enough that a prudent government should take action, not only as you were suggesting on CFCs, but on carbon dioxide, on methane, and on nitrous oxide?

Dr. CICERONE. Yes. Early this morning your other constituent here, Steve Schneider, mentioned that we know enough to take action if those actions are useful for other purposes at the same time.

And energy conservation, which is probably step number one, as you well know, Senator Wirth, is advantageous to us and to the world for so many reasons that we really should get on with that.

Senator WIRTH. Dr. Woodwell.

Dr. WOODWELL. Yes, absolutely. I think that we are long beyond the point where we should have started taking action. The issue of conservation of energy is real enough, but it is going to take at least a 50 percent reduction in the use of fossil fuels over a decade or so to move effectively into a position where we are not even safe, but reducing the risk of the problems that I laid out and others laid out.

Senator WIRTH. Dr. Ramanathan.

Dr. RAMANATHAN. Yes, I agree. As far as the CFCs are concerned, we know enough about them to talk about a complete phaseout in the near future.

As far as the carbon dioxide, again, we know enough about the greenhouse effect and the warming issue to talk seriously about energy conservation, very significant steps should be taken.

Senator WIRTH. Mr. Chairman, it seems to me, that just adds, further weight to the points that you and so many of us have been making for such a long period of time. From the perspective of the Congress, it is time for this country not only to act, but for this country to reassume a role of leadership among the western nations and around the globe.

Unfortunately, we have seen just the opposite. Despite George Bush's statements when he came into office that he was an environmentalist, despite a speech that he gave last summer, since the election in November we have seen almost no action at all.

Late last fall we saw the Administration quash the inclusion of consideration of global warming in environmental impact statements.

After Secretary Baker's welcome statement in January, we have seen absolutely nothing come out of the Administration in terms of their response to the Intergovernmental Panel on Climate Change. The Europeans have been way ahead of us on chlorofluorocarbons, and we have been really, in fact, scrambling to catch up.

When Prime Minister Bruntland was here last week, she attempted to talk to the President about global warming and apparently could not. Reports of that discussion indicate that they did not have any kind of a reasonable discussion on this issue, it kept being diverted away.

Just last Friday, Senator Gore, you cosponsored an amendment with me and many other members of the Senate to urge the Administration to act on the global climate convention as part of United States responsibilities as chairman of the response strategies working group for the panel on climate change.

And we met with enormous resistance from OMB, enormous resistance just to the idea of the United States, with its responsibilities as the leader of that response strategies working group, doing anything at all.

The response has come back from the Administration over and over: Do not do anything.

Now, it seems to me that what this hearing has done, Senator Gore, is to once again get us right to a watershed. Is the Administration going to be serious about this or not?

Now, it is very painful. You and I would like to work with them and like to get this job done in a reasonable and cooperative fashion, but if, in fact, we are going to continue to be stonewalled, we are going to continue to be met with resistance to doing anything, if we are going to continue to be met by what it seems to me to be absolutely unfounded responses which suggest that the evidence is not in, we are not going to get anywhere.

And so the time has come, it seems to me, for us to move to a question of a greater confrontation with them, and to try to push them and maybe embarrass them into action if, in fact, they cannot be led to action by a more reasonable approach.

I would just finally say, Mr. Chairman, if the Administration keeps saying to us—and they have said that to us on the Energy Committee as I know they have said that to you on the Commerce Committee—if the Administration keeps saying they are not sure about the evidence, why do they not come to a hearing like this? Why do they not ask all of you to come into the White House and talk to them? Why do they not ask you all to come into the Office of Management and Budget and talk to them? They have not made that kind of an effort at all.

These hearings have occurred over and over and over again, and I think the question is where have they been? What have they been doing. They have had 100 days in this Administration, and presumably they were examining a little bit of that evidence before this 100 days began in January.

So, Mr. Chairman, I thank you again for your leadership on this. Thank you for including me in this, and I think the time has come for us to just put this up more highly in the lights, and maybe we are going to have to follow a bit of a tougher and different strategy with a group of people that apparently do not want to listen. I thank you very much, Mr. Chairman, and once again thank the panel.

Senator GORE. Thank you. We appreciate you being willing to come here today very, very much. Thank you.

Our third panel consists of Dr. Stephen Schneider, who will make a repeat visit to the witness table. Please come forward at this time. Dr. Jerry Mahlman, Director of the Geophysical Fluid Dynamics Laboratory at the National Oceanic and Atmospheric Administration, and Dr. James Hansen, Director of the Goddard Institute for Space Studies with NASA. If the three of you would come to the witness table, we would appreciate it.

We would like you to keep your opening statements at a minimum because there are a number of questions we are going to want to pursue in the follow-up periods. We will go first with you, Dr. Hansen, then Dr. Mahlman, and then Dr. Schneider. And then we will save our questions until the conclusion of the panel.

First of all, let me welcome you, Dr. Hansen. I had the first hearings in Congress on the greenhouse effect more than eight years ago, and you were a witness at those hearings, Dr. Schneider. This whole issue has come a long way since then. All of the talk about uncertainty today is nothing compared to what it was back then. But you all are good friends as well as outstanding scientists, and I might say you demonstrate no little courage as well. We will get into a lot of other matters after we get through with the testimony. First of all, Dr. Hansen, we would like you to lead off. Welcome and please proceed.

STATEMENT OF DR. JAMES HANSEN, DIRECTOR, GODDARD INSTITUTE FOR SPACE STUDIES, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, NEW YORK, NY, ACCOMPANIED BY DR. STEPHEN H. SCHNIDER, SECTION HEAD, INTERDISCIPLINARY CLIMATE SYSTEMS SECTION, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, BOULDER, CO; AND DR. JERRY D. MAHLMAN, DIRECTOR, GEOPHYSICAL FLUID DYNAMICS LABORATORY, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, PRINCETON, NJ

Dr. HANSEN. Thank you. My testimony is based on research carried out with my colleagues at NASA Goddard Institute for Space

Studies located at Columbia University. But the opinions I express represent our scientific conclusions, not necessarily NASA policy.

Since 1958 the international geophysical year when Keeling began to make accurate measurements, atmospheric carbon dioxide has increased 11 percent, nitrous oxide about 7 percent, methane 30 percent, and the chlorofluorocarbons by a factor of 20.

We know the infrared properties of these gases, so we can compute the radiative heating of the earth's surface which they cause. It is 1.1 watts per meter squared.

Now, this small light bulb which I have here which I took off our Christmas string at home has a power of 1.1 watts. So, the heating of the earth due to the gases added in the past 30 years is equivalent to having a bulb like this shining down on every square meter of the earth's surface, day and night, year after year and getting brighter each year.

Now, at first glance, it is not obvious whether this heating is important. But consider that the earth absorbs 238 watts per meter squared. So, just the gases added in the last 30 years are one half of 1 percent of the energy that we get from the sun, and in 50 years it will be 2 percent of the energy we get from the sun if we continue along a path of business as usual for trace gas growth rates.

This amount of heating is important. It affects the temperature on the surface, the evaporation from the ground and the temperature and evaporation on a global scale affect the winds, the cloud cover and the rainfall and in turn these affect the oceans—the ocean circulation. That is why we need global models, because we need to analyze the interactions and feedbacks of the entire climate system.

One of the things that we learn from the models, by the way, is that this initial small forcing is magnified by feedback processes which we believe to be in the range of a factor some place between 1.5 and 4.0.

Now, the first point that I want to stress is the value of using models to study basic climate processes, as opposed to making predictions for Des Moines, Iowa or any other specific location. Models are not capable of accurate local climate predictions, but they can be used to help us understand some of the regional implications of global warming.

An example which we are beginning to study is shown on my first viewgraph. This shows—my first viewgraph, if it does appear——

Senator GORE. The overhead projector just broke down, I am informed, so I am sorry about that. We will try to get it fixed.

Dr. HANSEN. Well, you can find in my——

Senator GORE. We saw an OMB official near the projector.

Dr. HANSEN. The figure which I was going to show is included in my formal testimony. It is a color plate in that testimony and what it shows is areas of brown and green, where brown is used to represent dry areas and green, wet areas.

What we find in our climate modeling is that the large-scale warming which all of the models obtain causes an increased frequency of both extreme droughts and extreme wet situations in the model. This result, an increase of both hydrologic extremes, is one which we believe must survive as the models become more and more realistic, because it originates in a straightforward way from the greenhouse surface heating and the increased temperatures.

The location of wet and dry regions fluctuates from year to year, but increased rates of evaporation cause both increased rainfall and drought intensification. Now, one implication of this result, if it is correct, is that as the greenhouse effect increases droughts will become more frequent at most low latitude and middle latitude land areas.

Although the expected pattern of the drought intensification may change as key elements in the climate models are improved, such as the ground hydrology, the moist convection in clouds and the model's resolution, we believe that it is very unlikely that this basic result will be altered and we believe that there is a potential for scientific consensus during the next several years if this approach of looking at the basic processes is pursued broadly.

Now, the second point that I want to make concerns climate surprises, which you asked us to speculate on. Surprises can be either pleasant or unpleasant. The potential unpleasant surprise which I worry about is the possibility that there could be some near-term regional manifestation of the greenhouse effect analogous to the antarctic hole in the ozone depletion and in particular, could we suddenly have much more frequent regional droughts as opposed to the gradual transition suggested by the climate models?

I have two reasons to suspect that possibility. First, there seems to be an association of drought with high temperature and northern hemisphere temperatures are now near the levels of the 1930s, a time of frequent severe drought. Second, our climate model has a positive cloud feedback in drought regions, reduced low-level cloud cover which leads to more sunlight coming in and higher temperatures and more evaporation.

But this cloud feedback is weak in our model and I sometimes wonder if the cloud feedback is not more accurately described by John Steinbeck. I was going to show on my next viewgraph a quote from Grapes of Wrath in which, just picking out a few phrases from that paragraph, he said the clouds that had hung in high puffs were dissipated. The sun flared down, the clouds appeared and went away and in a while they did not try any more.

Well, if his description of clouds is more accurate than the crude cloud simulation in our model, then our present model underestimates the rate at which droughts can potentially intensify. To evaluate this issue we need to put realistic cloud physics into the models and we need good observations of the clouds in both drought regions and nondrought regions.

The third point that I want to make is a pleasant one. It also is illustrated on a viewgraph. I will have to tell you what was on that viewgraph. It shows that the production of CFCs were increasing about 10 percent a year for decades until 1974, when concern emerged about the possible impact of CFCs on the ozone layer.

If that growth rate had been maintained, the greenhouse effect of CFCs would now exceed that of carbon dioxide, which was shown on a bar graph on my third viewgraph and it is in my written testimony. But the environmental concerns of consumers and Congress caused a dramatic change in CFC production growth rates.

I think both consumers and Congress deserve credit for that action, which greatly reduced both the present and the future greenhouse effect and the ozone problem and that graph also illustrates very clearly the impact of breaking from a path of exponential growth of emissions. It is not necessary to eliminate emissions in order to have a very large impact on future greenhouse climate forcing.

My final point concerns what is needed to develop the understanding and the modeling capability for a greenhouse climate change. In my personal opinion, the primary need is brainpower. Observational hardware and large computers are important components in a balanced research program, but their effective use is critically dependent on the existence of appropriately trained and supported manpower which does not now exist.

An appropriate analogy, I believe, is the brainpower requirement which existed in the 1960s, when the United States developed a space science capability. Then, the government supported hundreds of traineeships at top graduate schools, also post-doctoral scientists and research at universities and government laboratories.

The challenge in the earth sciences now is at least as great as that of the space sciences in the 1960s. We must begin to attract and support more of the best and the brightest students if we want to achieve the understanding and predictive capability for global change.

Thank you.

Senator GORE. Thank you very much. We are going to hold off on questions. I have a number of things to pursue with you, but let us get the other two statements and then we will ask questions of all three witnesses.

Dr. Jerry Mahlman is the Director of the Geophysical Fluid Dynamics Lab at NOAA. Welcome, Dr. Mahlman. Please proceed.

Dr. MAHLMAN. Thank you, Mr. Chairman. As you are well aware, the carbon dioxide greenhouse problem has been with us for virtually a century. The collective influence of the other greenhouse gases have interestingly enough been with us for over a decade now, after the revolutionary paper by our colleague Dr. Ramanathan, published in 1976.

The question of how to predict climate has been also with us for a long time. At our laboratory, we have been in the process of assembling pieces of a complete climate model for almost 30 years and interestingly enough we have been involved for 20 years in the problem of assembling coupled ocean atmosphere models.

Over that time we have learned a lot—us and the other scientific community. We have also learned a lot by what we do not know and today I would like to take this privilege that you have given me to tell you what I think the models can do well and what I think they cannot do so well and these models are, as described by Dr. Schneider, global comprehensive self-consistent mathematical models of the climate system.

In order to do this, I would like to introduce you to the concept of climate confidence and probability and I will have four levels of confidence about various features that the models are indicating.

My top category is what I would call virtually certain use in exactly the same context that Steve Schneider said earlier. The next lower category is what I would call very probable, betting I would say nine out of 10, and a lower category is what I would call probable and there I am talking about a subjective determination of betting odds is something like two chances out of three. My lowest category is uncertain. Namely, there is a hypothesized effect that we in the climate modeling community have not been able to evaluate properly.

The first virtually certain climate prediction that I think we can all make is the indication that the models say of very large cooling in the stratosphere, that this cooling rate is much larger than what we are predicting at the ground and essentially there is nothing that we can think of that makes it go away.

Interestingly enough, one thing that makes it a little bit worse is the recognition of the antarctic ozone hole phenomenon. In fact, there is already a change in the spring climatology of the lower stratosphere of the order of a 10 degree Celsius cooling as a result of that phenomenon. That was a climate surprise, but it is in the context of a no-surprise region, where we already expected the climate cooling effect to be very, very large there.

In the very probable, or nine out of 10 odds category, I would put down the concept of a global surface warming over the next century as being very probably, or easily a nine out of 10 shot. Dr. Schneider mentioned the likelihood of a global mean precipitation increase as also probably better than nine out of 10 odds and that is a statement that says essentially nothing about the local distribution of precipitation, which it has already been indicated is far less certain.

The potential of an arctic winter surface warming of a substantial magnitude greater than the global average accompanied by a reduction of sea ice in high northern latitudes is also, I would put in the very probable category.

Interestingly enough, as we move into the categories in which you and all members of the public community are interested in, our confidence begins to decrease markedly, sometimes plummet and that is the questions of regional climate change. The reasons for that I think are very logical, very straightforward, and scientifically defensible.

I assure you that the regional climate uncertainty problem is one of significant barriers in understanding and modeling the physics of the process. It is not because we have not been paying attention. They fall into four categories that I will speak briefly about. One is model resolution. Two, model physics. Three, the inclusion of the ocean, and four, the vexing effect of climate variability. I will give examples of each of these.

The first is the current resolution—or the grid size, if you will—of climate models, is of the order of 500 kilometers, or roughly 300 miles on a side. In order to have serious regional resolution of these models we probably would seek something on the order of 60 miles on a side, because then you are talking about bite-size pieces of geography.

The computational cost to have a climate model at that resolution is a factor of 500 greater than the current climate models can permit, simply because of a lack of sufficient computer power.

The second issue is one of details of land surface processes and surface physics and Dr. Schneider already indicated a result of predicted mid-continental, midsummer reductions of soil moisture from one of the models from our laboratory. Notice that I put that in the probable category—a two out of three bet, even though it is a result from our own model.

There are situations that one can think of in the model in terms of its prescription of the physical processes that make it entirely possible that the real world will evolve in a different way than indicated by the mid-summer continental dryness issue.

Another possible climate surprise is what happens when these climate models put a real ocean below them, rather than the finessed ocean, or mixed-layer ocean, that most of us have dealt with in order to keep the problem physically and computationally trackable.

Our laboratory has completed a 200 year integration of a coupled atmosphere ocean climate model with a full ocean below at these very modest resolutions, consistent with the rest of the climate modeling community and we get one of the first climate surprises that is potential for the next generation of calculations.

That we see the high latitudes of the northern hemisphere warming up more than the global average but, interestingly enough, the circum-Antarctic region in these calculations is refusing to warm up for virtually a century and the reason for that in the model, and there is some corroborating evidence from the real world, is that this is a region of upwelling of effectively older water in the circum-Antarctic ocean that effectively provides a thermal buffer against the greenhouse effect in those regions.

So the models are essentially saying that the high latitudes of the southern hemisphere near Antarctica, at least in this one calculation which has not been duplicated, may indeed be a significant climate surprise. That obviously has real implications, positive and negative for the possibility of quantifying the sea level rise problem.

More recent analysis has shown that in the coupled atmosphere ocean model as part of the transient response to gradually increasing greenhouse gases, that the ocean circulation adjusts locally to produce hot spots and cool spots in the ocean which affects the local climatology here.

We cannot dignify these early calculations by calling them climate predictions at this time, but it does provide some insight into the potential physical processes being overlooked in the current generation of models. It will take easily another five years to sort this out in any significant way.

The final source of frustration and uncertainty in our analysis and prediction of regional climate effects is due to the problem of climate variability itself, that many users of climate prediction information are exceedingly frustrated with us as a community because they will inevitably say, you scientists give us the same old story.

You talk about long-term global averages. Who cares about the global average? We want to know what is happening here. We want to know what is happening where we live and this is a problem that will remain with us for a long period of time, for a very simple reason. The above examples will make this an extremely difficult problem, but the final example is the climate variability itself.

One of the reasons we emphasize long-term global averages is that it helps us separate the so-called noise from the climate system from the signal of the greenhouse warming in that the smaller the region you look at and the shorter the time you average over, the higher the likelihood that the region will be dominated by climate noise rather than greenhouse signal.

So all of these lead to a final, very confident prediction, is that the attention of the user community—yourselves and others—will demand information from those of us who do climate models at a rate that is significantly higher than we can deliver on a particular time.

The reason for this is because the product is so valuable and the time is so extended and the degree of difficulty is so high, that when we get into regional climate change issues the uncertainty will remain high. The possibility for climate surprises both on the low side and the high side are very real.

[The statement and questions and answers follow:]

TESTIMONY OF

J. D. MAHLMAN, DIRECTOR
GEOPHYSICAL FLUID DYNAMICS LABORATORY
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

BEFORE THE

SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND SPACE
COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION

UNITED STATES SENATE

MAY 8, 1989

Mr. Chairman and Members of the Subcommittee:

My name is Jerry D. Mahlman. I am the Director of the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA), in Princeton, New Jersey. It is a pleasure for me to offer perspectives on climate model estimates and their current level of uncertainties. For over thirty years our laboratory has been a world-leading institution in mathematical modeling of the earth's climate.

For many decades scientists have known that a buildup of carbon dioxide (CO_2) in the atmosphere has the potential for warming earth's climate through the so-called "greenhouse" effect. Over the past 10 years, awareness has grown that other greenhouse gases can contribute in total to climate warming at a level comparable to that of CO_2. These include human-produced chlorofluorocarbons (CF_2Cl_2, $CFCl_3$, and others), methane (CH_4) and nitrous oxide (N_2O). The atmospheric concentrations of these gases are currently increasing at a rate sufficient to produce substantial atmospheric consequences over the next century.

These other greenhouse gases are well known to contribute to very significant expected changes in the atmospheric ozone structure and amount. Their potential to add to the CO_2 climate warming effect is not as universally appreciated. Today I will emphasize only the expected climatic effects of greenhouse gases.

The information that I will present is derived from three-dimensional mathematical models of the climate system. A schematic of the various relevant physical processes is given in Fig. 1. Such comprehensive global climate models have been under intense development at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) for nearly 25 years. Climate models have grown steadily in scope, complexity, and computational resolution over that period. Accompanying this growth is an improvement in the ability of the models to simulate the current climate. Accordingly, modeling atmospheric responses to changing conditions (e.g., seasonal and daily cycles, different planets (Mars and Venus), ice age conditions) has become progressively more accurate. Unfortunately, substantial uncertainties remain due to deficiencies in scientific understanding and insufficient computer power. However, significant progress is expected on both fronts over the next ten years. Computer power is increasing while its relative cost is still decreasing. The impact of model dependence upon computer power may be seen in

Fig. 2. Deficiencies in scientific understanding of such areas as ocean circulation, cloud processes, land surface processes, and chemical interaction will continue to yield gradually to intense scientific inquiry. In addition to the models, adequate data are necessary to evaluate results of the model calculations.

In spite of climate model limitations, simulations of the effects of increases in the greenhouse gases permit a number of plausible inferences to be drawn today with considerable confidence. In most model studies to date, atmospheric CO_2 concentrations have been doubled (e.g., from 300 to 600 parts per million) and then maintained at that concentration until a new equilibrium climate is established in the model. Typically, such a model just includes the atmosphere; the only effect of the ocean is its effect as a heat reservoir. We expect such model results to apply reasonably well to a combination of CO_2 and other trace gases where the total effect on the radiation budget is equivalent to a doubling of CO_2. Moreover, because of the now recognized effect of the other greenhouse gases, calculations using doubling of CO_2 are now thought to be relevant (from a societal impact perspective) for conditions sometime in the middle of the next century. In this presentation, I will avoid detailed scenarios. Rather, I will emphasize the kinds of expected impacts and my best estimates of their current scientific uncertainties.

Some of the possible climate responses to increased greenhouse gases are regarded to be rather well understood; others remain controversial. Scientific confidence is presented here in general terms. I will give my estimates of confidence levels based upon current models. To give some guideline, by "virtually certain" I mean that there is near unanimous agreement within the scientific community that a given climatic effect will occur. Here, "very probable" means, I believe, greater than about a 90 percent (9 out of 10) chance, and "probable" implies more than about 67 percent (2 out of 3) chance. By "uncertain" in this context, I refer to an effect that has been hypothesized, but for which there is a lack of appropriate evidence. I list below, in decreasing order of current scientific confidence, some important model-predicted climate changes due to increased greenhouse gases. (This list is similar to that in National Research Council, 1987.)

* Large Stratospheric Cooling (virtually certain)
  A reduction in upper stratospheric ozone by chlorine compounds will lead to reduced absorption of solar radiation and thus, less heating. Increased stratospheric concentrations of radiatively active trace gases will increase infrared radiative heat loss from the stratosphere. Decreased heating and increased cooling will lead to a marked lowering of upper stratospheric temperatures, perhaps by 10° - 20°C (Fig. 3).

* Global-Mean Surface Warming (very probable)

  For a doubling of atmospheric CO_2 (or its radiative equivalent from all of the greenhouse gases), the long-term global-mean surface warming is calculated to be in the range of 1.5 to 4.5°C (see Figs. 3 and 4). The most significant uncertainty arises from difficulties in modeling the feedback effects of clouds on climate change. The actual rate of warming over the next century will be governed by the growth rate of greenhouse gases, natural fluctuations in the climate system, and the detailed response of the slowly responding parts of the climate system, i.e., oceans and glacial ice.

* Global-Mean Precipitation Increase (very probable)

  As the climate warms, the rate of evaporation increases, leading to an increase in global-mean precipitation. Despite this increase in global-mean precipitation, local regions might well experience decreases in precipitation.

* Northern Polar Winter Surface Warming (very probable)

  As the sea ice boundary is shifted poleward, the models predict a significantly enhanced surface warming in winter polar regions (see Fig. 5). The greater fraction of open water and thinner sea ice is calculated to lead to an effective winter warming of northern polar surface air by as much as 10°C relative to the current climate.

* Reduction of Sea Ice (very probable)
  As the climate warms, total sea ice is expected to be reduced in response to warming in high latitudes of the Northern Hemisphere. However, new GFDL model results with a fully interactive ocean indicate little warming may occur at high Southern Hemisphere latitudes, thus leading to little change in sea-ice cover there (Fig. 6). Also, see above.

* Northern High Latitude Precipitation Increase (probable)
  As the climate warms, the increased poleward penetration of warm, moist air should increase the annual-average precipitation and river runoff in high latitudes.

* Summer Continental Dryness/Warming (probable)
  Several model studies have indicated a marked decrease of the soil moisture over some mid-latitude interior continental regions during summer. This drying is mainly caused by an earlier termination of snow melt and rainy periods, and thus, an earlier onset of the normal spring-to-summer reduction of soil moisture. For a comparison of this effect in doubled and quadrupled CO_2 atmospheres, see Fig. 7.

* Rise in Global Mean Sea Level (probable)
  A rise in mean sea level is generally expected due to thermal expansion of sea water in the warmer future climate. Far less certain are the contributions due to

melting and calving of land ice. Predictions of actual rise rates for mean sea level remain difficult and controversial.

* Regional Vegetation Changes (uncertain)
  Climatic changes in temperature and precipitation of the kinds indicated above must inevitably lead to long-term changes in the surface vegetative cover. The exact nature of such changes and how they might feed back to the climate remain uncertain.

* Tropical Storm Increases (uncertain)
  A number of scientists have suggested that a warmer, wetter atmosphere could lead to an increased number and intensity of tropical storms, such as hurricanes. However, tropical storms also are governed by other factors such as local wind structure. At the present time, this effect has not been satisfactorily addressed in a climate model due to the relatively small size of tropical disturbances.

* Details of Next 25 Years (uncertain)
  The results given above describe calculated changes in equilibrium climate due to hypothetical large changes in greenhouse gases. In actuality, these gases are increasing gradually with time. Initially, much of the excess heat is absorbed into the oceans, perhaps in complex ways we do not yet understand well. Further, we

can expect that natural, decadal-scale climatic fluctuations due to interactions between the atmosphere and oceans will continue to occur. The midwestern drought in the 1930's and the high water levels of the Great Lakes in the 1980's are good examples of such climatic fluctuations. On these shorter time scales, it is likely that the natural fluctuations would reduce or enhance the expected greenhouse warming signals (Fig. 8). Until these decadal-scale fluctuations are understood or predictable, it will remain difficult to diagnose the specific signals of permanent climate change as they evolve over the next quarter century. Moreover, detecting climate change signals becomes even more difficult when smaller regions and/or shorter periods of time are considered.

Even though the above uncertainties are daunting, important advances have already been achieved in the observation, understanding, and modeling of the climate system. The current models are capable of simulating the gross features of geographical and seasonal variations of the current global climate. Furthermore, some of these models have achieved successful simulations of the very cold climate of the last glacial maximum and the extreme temperatures found on other planets. These overall scientific advances have initiated the current public awareness of climate change and its potential implications for the future of the world. This awareness has escalated the need for reliable climate predictions, accurate assessments of the causes of the actual changes occurring, and an ability to distinguish human-produced climate change from longer-period natural variations. Although progress has been made, as noted above, significant deficiencies remain in the capability of the scientific community to address these needs.

Much more effort must be expended world-wide toward providing a climate monitoring and measuring system characterized by careful instrument calibrations and intercomparisons and a commitment to continue measurements over many decades. Focused research into climate processes must be accelerated so that theories can be formulated and re-evaluated in the light of newer information. To reduce climate modeling uncertainty, it is imperative that climate modeling efforts receive state-of-the-art supercomputing resources and the scientific talent to exploit those resources.

The President's FY 1990 budget highlights the start of a long-term, interagency commitment to address these concerns through the U.S. Global Change Research Program. This program is described in a report entitled Our Changing Planet which accompanied the President's Budget. The goal of this program is to establish the scientific basis for national and international policy-making related to natural and human-induced changes in the global climate system. NOAA expects to utilize its scientific resources and talents to contribute to accomplishing this goal.

Through careful long-term research on observation, modeling, and analysis, uncertainties will decrease and our confidence for predicting details of the climate system and its changes will gradually improve. A final, very confident prediction is that the societal need for accurate and detailed climate predictions will increase as fast or faster than the scientific community can provide them. The effort to meet these societal challenges will require the combined forces of the world scientific community in a sustained effort spanning decades.

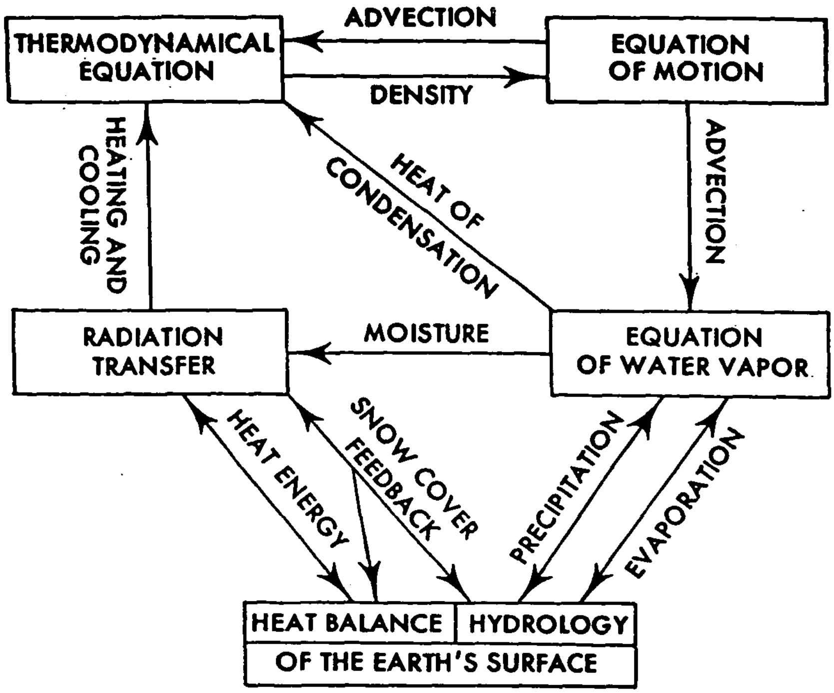


Fig. 1. Simplified schematic diagram illustrating some of the interactive atmospheric processes governing earth's climate system. A proper climate model must account for all of these processes (and more) consistent with the laws of physics at a large number of points on the model "earth".

MODEL COST AND REGIONAL CLIMATE CHANGE

Current Climate Model Resolution (No Ocean)

5° Latitude (300n miles) x 5° Longitude x 10 levels

(36x72x10 = 25,920 grid points)

Improved Resolution

2.5° Latitude by 2.5° Longitude x 20 levels

(207,360 grid points x 2) (doubled time steps)

16 times the "cost"

Exploratory Resolution

1° Latitude by 1° Longitude x 40 levels

(2,592,000 grid points x 5) (quintupled time steps)

500 times the "cost"

Fig. 2. Illustrative example of the strong demands on computer resources as a climate model's grid resolution is increased.

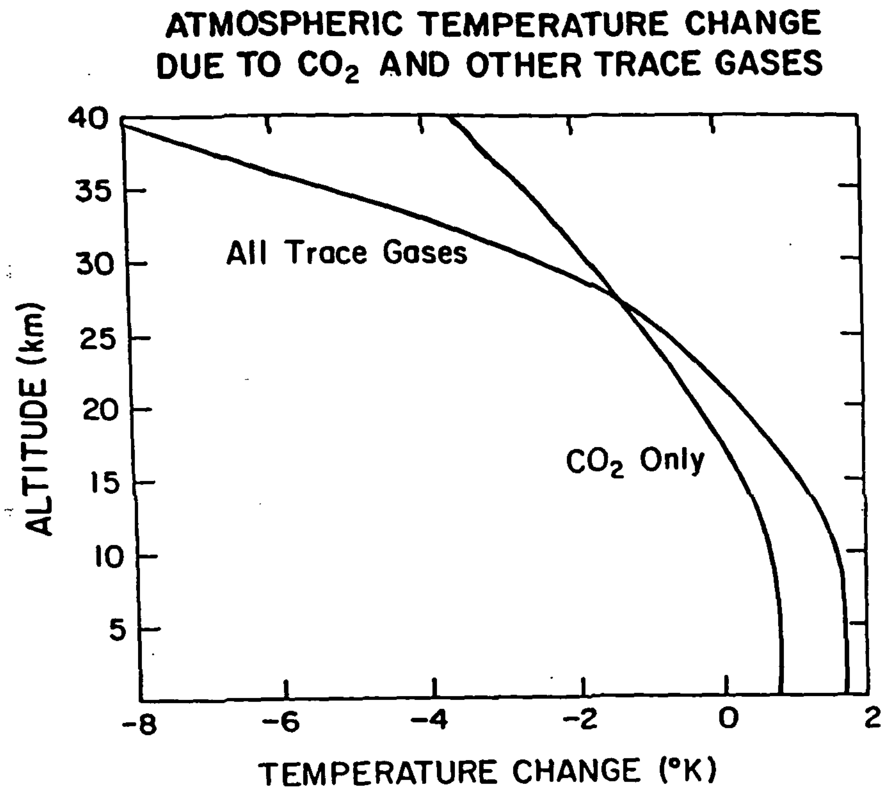


Fig. 3. Estimate of the global-average temperature change (°C) for the year 2030 based upon projected trace gas trends. "CO_2 Only" includes only effects changing CO_2; "All Trace Gases" includes effects of changing CO_2 as well as all the other increasing greenhouse gases (after Ramanathan, et al., 1987).

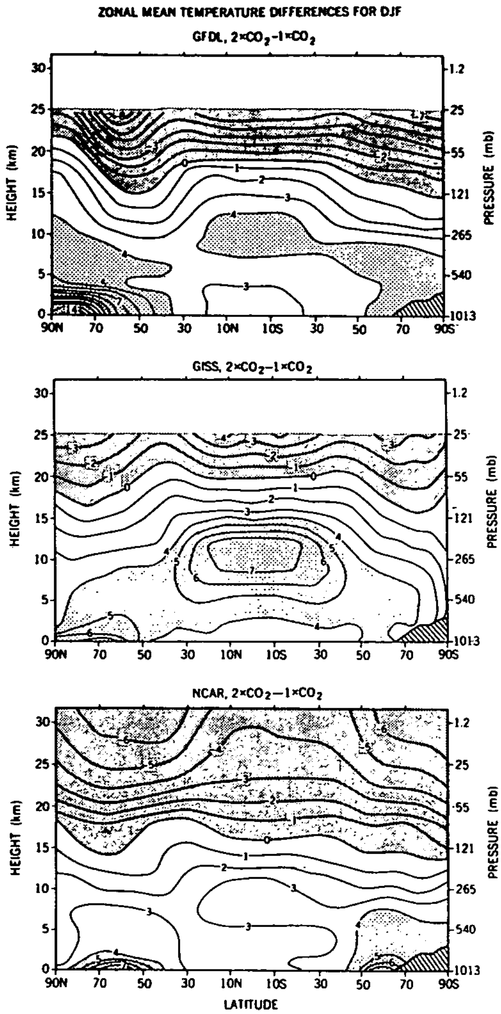


Fig. 4. Latitude-height cross-sections of December-January-February mean temperature change (°C) for a doubled CO_2 world compared to today's climate for 3 different models. Top picture is for Geophysical Fluid Dynamics Laboratory (NOAA) model; center picture is from Goddard Institute for Space Studies (NASA); bottom picture is from National Center for Atmospheric Research (from Schlesinger and Mitchell, 1985).

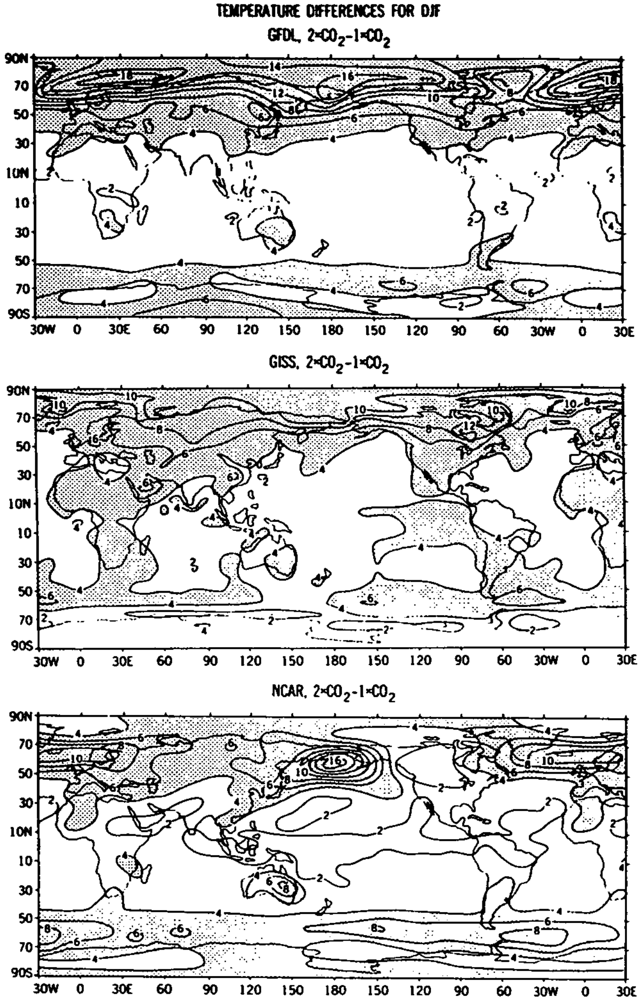


Fig. 5. Latitude-longitude cross section of December-January-February mean surface temperature change (°C) due to a doubled CO_2 as calculated by the three different climate models described in Fig. 4 (from Schlesinger and Mitchell, 1985)

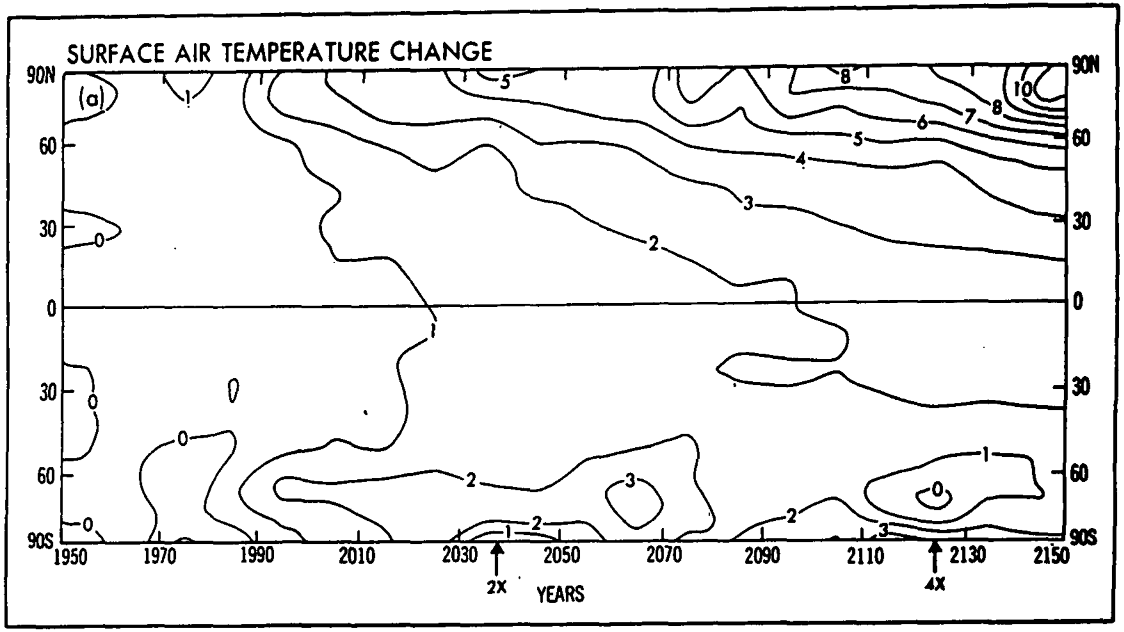


Fig. 6. Time evolution of temperature change (°C) in a GFDL/NOAA coupled atmosphere-ocean model due to a 0.8% per year buildup of CO_2. 2X (4X) denotes the year when the prescribed CO_2 content is double (quadruple) the initial value. The resistance of the southern high latitude region to greenhouse warming illustrates the potential of ocean circulation to yield significantly different results than those indicated in the previous generation of models.

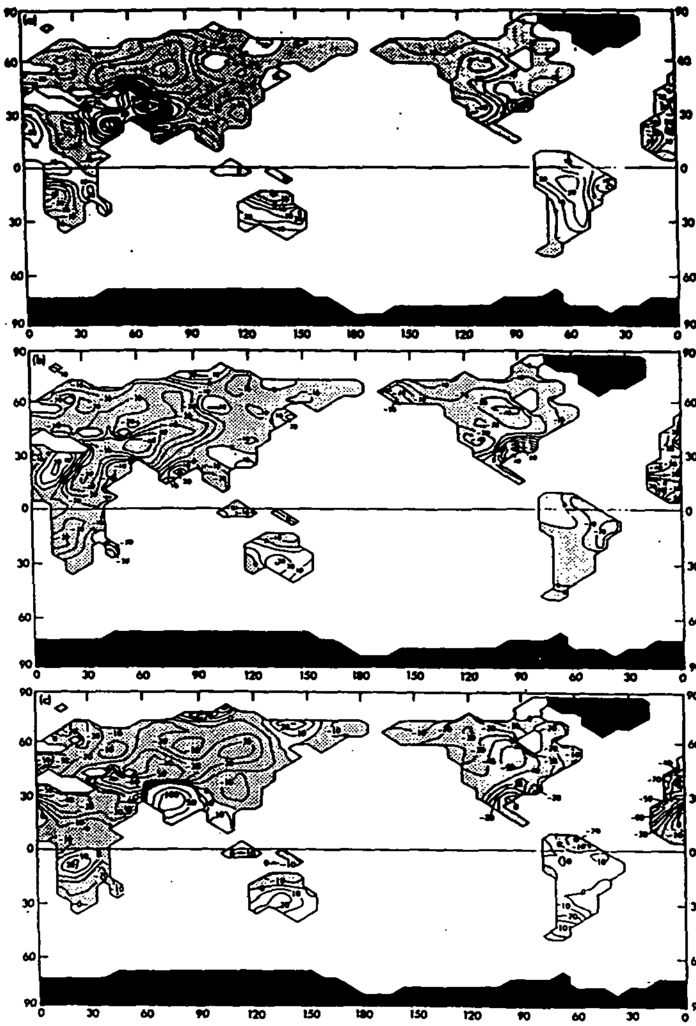


Fig. 7. GFDL model calculation of changed soil moisture (%) for months of June-July-August. Upper picture is for doubled CO_2; lower picture is for quadrupled CO_2. Darkest shading indicates decreases greater than 20% (after Manabe and Wetherald, 1987).

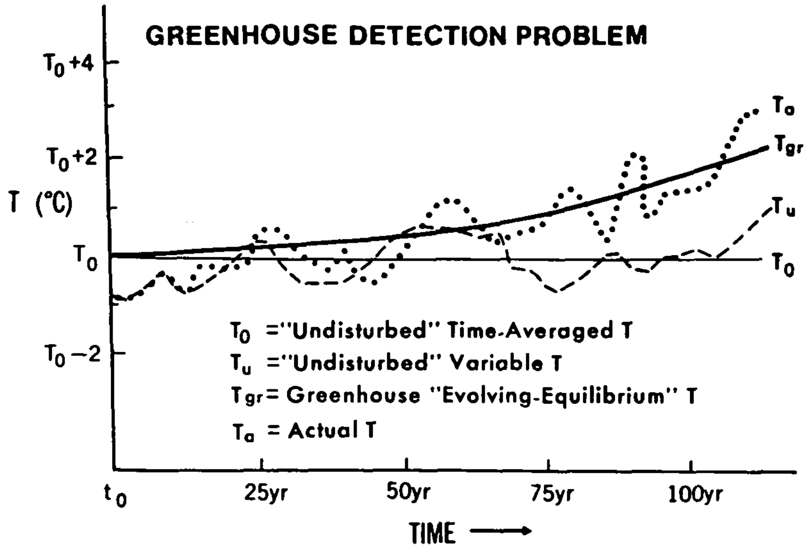


Fig. 8. Schematic illustration of the greenhouse warming detection problem. The thick line (T_{gr}) represents evolution of a hypothetical "evolving equilibrium" greenhouse temperature warming. The thin line (T_0) is an assumed undisturbed time-averaged temperature. The dashed line (T_u) represents the actual temperature variation in an undisturbed climate. The dotted line (T_a) is the actual fluctuating signal for an earth with gradually increasing greenhouse gases. Note that it can take many years to separate a fluctuating greenhouse signal (T_a) from the undisturbed fluctuating signal (T_u).

Question from Senator Kasten to Dr. Jerry D. Mahlman, Geophysical Fluid Dynamics Laboratory/NOAA, at an 8 May 1989 Senate Subcommittee on Science, Technology, and Space Hearing on "Possible Climate Surprises"

Senator Kasten:

"I know that your facility has a request in the NOAA budget this year for $3.1 million to upgrade your computer capability from Class 6 to Class 7. Given the importance of the modeling which we are focusing on today, could you give us some examples of the increased capability that this Class 7 computer would provide for you? Could you comment on the importance of such an upgrade to your future mission?"

Reply from Dr. Jerry D. Mahlman:

Background

To address the question properly, I must set the context by discussing some aspects of the Department of Commerce request for an upgrade to GFDL's Class VII computer system. First, tne amount of computer power justified through GFDL's service to NOAA's priority programs and through a careful benefit/cost analysis is a factor of 30 over the current system. Second, the dollar amount requested due to budget stress and a desire to maximize the benefit-cost ratio provided for only a factor of 10 increase in computer power.

Tne purchasing power in the original request of $2.8 million per year and a one-time increase in FY 1990 of $1 million for conversion costs has diminished due to two new factors. The Commerce request of $2.8 million per year has been reduced to $2.1 million per year by OMB. Also, the recent cancellation of the ETA-10 supercomputer likely will have the undesirable side effect of reducing the competitiveness of the remaining supercomputer industry, thereby reducing the effective purchasing power of the government's investment.

The effect of these developments could reduce the computer power increment obtainable under the current OMB authorization to as little as a factor of 5. Such a degradation of power from the original justification would significantly reduce GFDL's capability to pursue the next frontier of climate (and weather) problems as described below.

Previous Advances

Each new generation of computers at GFDL has produced important new advances. For example, installation of the current computer at GFDL allowed a number of advances including: construction of a high resolution, "eddy resolving" ocean model for climate applications; the first realistic geography, coupled atmosphere-ocean climate model; simulation of interannual variability such as the El Niño-Southern Oscillation; a physically comprehensive model of the stratosphere; major advances in global weather forecasting including inclusion of GFDL model components into the National Meteorological Center operational forecast model; and pioneering models of hurricanes and winter storms.

Expected Advances

The most obvious example that the proposed factor of 10 increase in computer power would provide is in regional and transient climate change modeling. The improved model spatial resolution and increased reliability of surface physical processes will both produce important increases in our ability to model and predict regional climate changes. Inclusion of self consistent ozone chemistry will become part of the climate model system. The enhanced computer capabilities will allow a far more systematic and credible attack on the extremely difficult, but central, problem of quantifying the role of cloud radiative feedback in the climatic response to increased greenhouse forcing.

Higher resolution ocean models will produce increasing confidence in modeling the complex role of ocean circulation and biogeochemistry in the climate system. This progress will lead to a better understanding and modeling of the role of the ocean in producing natural climate variations on the scale of years to perhaps centuries. Also, the increasingly reliable coupled ocean-atmosphere models will allow a pioneering exploration of the new frontier of weather/climate prediction on time scales from a month to possibly years.

Finally, a number of important advances are expected in the storm dynamics and weather forecasting areas. These include: global extended range weather/predictions; hurricane track and intensity forecasts; and better predictive models for local regions.

These expected improvements are at the heart of GFDL's role in fulfilling NOAA's mission requirements. This computer upgrade is essential if GFDL is to continue its world-leading role in climate, ocean, and weather modeling research.

Senator GORE. Thank you very much. Dr. Schneider, if you could briefly bat cleanup here and give us a short summary of how to improve global climate models we would appreciate it and then we will get right to the questions.

Dr. SCHNEIDER. Mr. Chairman, I will give you a pleasant surprise. I will end way before my orange light. The remaining point I think we need to emphasize since virtually everything that you have asked for in your invitation letter has been handled nicely by my colleagues, is the question of timing.

How long is it going to take us to be able to resolve the important uncertainties about regional climate effects—where is wetter and drier, for example—relative to the time it takes to implement policies to do something about that and relative to the time it takes for the system to perform the experiment.

Well, I prepared in my written testimony a table—Table 1—which I had done with my colleagues Peter Gleick and Linda Mearns, which we had done for a project for the American Association for the Advancement of Science, funded by the National Science Foundation, on water and the climate.

We projected into the future annual global average changes in temperature, sea level precipitation, soil moisture and so forth, as well as regional issues and we came up with the usual results of warming on the order of several degrees and sea level rise from 10 to 100 centimeters and precipitation increase globally but not necessarily locally and so forth. But beyond that we tried to add a category which was more subjective, which was our intuitive estimated time for research that leads to a consensus.

Now, in temperature, on the magnitude we put down zero to five years, because it was our opinion that we already have—and I think we have heard that from most of the witnesses today—a strong consensus that it is very likely that we will have warming.

On sea level we had numbers like five to 20 years and part of the reason for that is the rate at which the oceans will rise depends upon where in the oceans they warm up. The oceans do not expand with heating uniformly. They expand more rapidly if the water is warm than if the water is cold, so there is some uncertainty associated with where it happens and also there is uncertainty with whether snow will build up in Antarctica and decrease in Greenland so that is why we have that timing of about a decade for large scale consensus.

But then in the other categories, the ones that are most important to human activity, the increase in likelihood of drying in midcontinent, for example—the probable category that Dr. Mahlman referred to which is so critical to agriculture, water supplies, health and so forth—we have a 10 to 50-year timeframe to build consensus.

The reason for that has been enumerated by my colleagues and by me earlier, which is that we simply have to run coupled models of the atmosphere, the oceans and the biota and the sea ice together and we have to run them with realistic increasing transient scenarios of greenhouse gases if we are going to get those details right, and 10 years to me would be optimistic at the current fragmented level of effort to be able to produce widespread consensus among atmospheric scientists on that problem.

So when someone suggests that we wait until we have more reliable information before we decide to react to that, we are talking about waiting on the time frame of a decade or two, in my opinion, before that kind of a consensus will build, and that is the time frame in which nature will begin to perform the experiment.

At the same time, we lock in infrastructure such as water supply projects, new power plants, refrigerators in China, which lasts on the order of decades, perhaps a half a century; and therefore decisions made now will be carried forward—the infrastructure decisions made now will be carried forward for 50 years.

So waiting 10 or 20 years ensures that we lock in much less efficient production than if we added some strategic logic and leveraged the system. From the technical point of view, we could accelerate the rate at which we reduce the uncertainty time perhaps from two decades down to one, but we could not even guarantee that because we must run those coupled experiments for which we have just begun experimentation.

Senator GORE. Thank you very much, Dr. Schneider.

Now we will have questions of the three witnesses on this last panel.

I would like to start with you, Dr. Hansen.

In your statement you respond to our request for information on our scientific understanding of global climate models and our effort to determine which effects are pretty well understood and which effects are subject to change as we learn more about the models.

You respond by saying, among other things, that as the models improve and more evidence becomes available, it is not very likely that scientists will change their conclusion that increases in greenhouse gases will intensify drought in the middle and low latitude land areas, like the Midwest of the United States.

I am puzzled that you also say on that same point on page 4 of your statement that you want to stress that you do not really believe that and that as the computer models evolve, that conclusion will very likely evolve and should not be regarded as reliable.

I think I know the answer to the question I am about to ask you, but why do you directly contradict yourself in the testimony you are giving about this scientific question?

Dr. HANSEN. Let me first rephrase exactly what we said in that regard because when I discussed this with my scientific colleagues, the slight rephrasing makes a difference.

What I said was we believe it is very unlikely that this overall conclusion drought intensification at most middle and low latitude land areas if greenhouse gases increase rapidly, will be modified by improved models. Now, that is what I believe, and that is what I wrote.

The last paragraph in that section which seems to be in contradiction to that was not a paragraph which I wrote. It was added to my testimony in the process of review by OMB, and I did object to the addition of that paragraph because in essence it says that I believe that all the scientific conclusions that I just discussed are not reliable, and I certainly do not agree with that.

In fact, the point I was trying to make in that section is that we are trying to pursue an approach of looking at certain processes where the conclusions will not be sensitive to the model details.

Now, the way that added paragraph is written, it implies that every time a model is rerun you will get a different answer, and that of course, if you looked at the exact climate in Des Moines, Iowa, you rerun the model with a different parameter, it is going to be a little different. But I was trying to focus on those broad conclusions which I think in my opinion will not be modified, and those include the large-scale warming and the drought intensification of most middle and low latitudes and increased intensity of extreme wet events, and those were the things that we focused on.

Now, a couple of things I want to clarify here in the preface to my testimony. We state that the testimony represents my scientific opinion, my scientific conclusions, not government policy, or a consensus of the scientific community.

So, I think with these qualifications I do not believe that the science aspects in the testimony should be altered. But, my only objection is being forced to alter the science.

I have—as a government employee I certainly can and do support what the policies are, and I do not object to review of the policy statements.

Senator GORE. So, the statements which were changed by OMB were not statements about policy. They were statements about the scientific data, correct?

Dr. HANSEN. That is right.

Senator GORE. Did you object when OMB forced you to put these words in the first person into your statement? They instructed you to use the pronoun "I" and to follow it with conclusions which were not yours but theirs about the scientific evidence, correct?

Dr. HANSEN. Well, I did try to get them to compromise on wording. For example, the "not reliable" is what I particularly objected and was unable to get them to change that.

I did notice this first person "I," and that is a little disturbing, but I did not actually try to get them to change that. They might have been willing to change that pronoun.

Senator GORE. Well, were there other parts of your testimony which they forced you to change?

Dr. HANSEN. The number of changes as these things go is actually not that large, but there was at least one other one which I think is worth mentioning. That was concerned with the—they added a sentence which says one point that remains scientifically unknown is the relative contribution of natural processes and human activities to the growth of trace gas climate forcings.

Now, I was able to get them to change the last part of that sentence to say "non-CFC climate forcings," because it is very clear that CFCs have no natural source. But, you know, even in the case of the growth of carbon dioxide and methane, it is pretty clear to scientists that in fact they are rising because of anthropogenic emissions.

I agree that the sentence is a scientifically correct sentence, but I would not have added that myself if I had not had it put in there for me.

Senator GORE. Well, every scientist that testified here today and every reputable scientist that I know of in the field supports your conclusion that this is primarily a human-caused phenomenon and that it is probably not an act of God that we have had nothing to do with.

OMB forced you to say well, maybe, we are not a significant cause of this at all that if it may be just forces of nature operating without a significant contribution from what we are doing.

Now, back to the first change that they forced you to make, A lot of farmers last year and a lot of other people began to wonder whether or not the unprecedented drought and heat wave had anything to do with the global warming which many of us have discussed for years.

The scientists have now concluded that while it is impossible to say that any given year is a direct result of a global climate trend, it is now possible to say with some certainty that the earth will warm because of what we are doing and specifically that there will be intensified drought because of this trend.

The Bush Administration is acting as if it is scared of the truth. They are acting as if they do not want the best scientists in the administration to come to Congress and give us the best knowledge that you can glean from the data.

If they forced you to change a scientific conclusion, it is a form of science fraud by them. If they forced the negotiators in Geneva to pretend that we need to know more before we act, that also is fraudulent. And if they substitute this kind of do-nothing policy for the promises of then-candidate George Bush, that, too, is fraudulent.

It seems to me that they have got a decision to make. Are they going to let scientists come up here and tell us the truth? Are they going to recognize the truth and then make the changes in policy required to respond to this emerging crisis? Are they going to keep the campaign pledges which they used in television commercials all over this country? And is this administration going to be committed to environmental protection or not?

These are the questions which come as a result of what has happened here. Let me just put it into its starkest form. They say in Geneva that no action is justified because we need more study, and then they say here in this hearing, do not tell the Congress what the studies are showing. Cover it up with a lot of vague denials that it has any reliability, and that is what they have ordered you to do.

I want to commend your courage in being candid in response to my questions about what your personal opinion really is about the scientific evidence. I appreciate that a great deal.

Dr. Mahlman, have you ever——

Dr. HANSEN. Excuse me, could I respond?

Senator GORE. Yes, please respond by all means.

Dr. HANSEN. You mentioned truth. We have to be careful to distinguish between truth and opinion.

Senator GORE. But truth is formed by the assessment of data. Our understanding of the truth is never perfect, but it is formed by a candid assessment of the most objective opinions we can gather, and if the scientists who are used to dealing with uncertainties in the data are forced to color their judgments and cannot give us the most accurate assessment of the evidence that they can possibly give us, but are forced to give us some politically colored version of their studies, then it makes it all the more difficult to find out what the truth is.

You know, in the Soviet Union they used to have a tradition of ordering their scientists to change their studies to conform with the ideology then acceptable to the state. And scientists in the rest of the world found that laughable as well as tragic.

Now, we are confronted with the most difficult environmental question humankind has ever faced and we are forced out of necessity to fashion policy on the basis of science that is incomplete and as we gain more information, we find more justification for toughening the actions.

I think we know enough already and a lot of other people believe that. But the Administration does not want to act. They want to sit still and do nothing, and as the evidence becomes clearer and clearer, they become more and more afraid of the scientists coming up here and telling us how much closer they are to certainty about what is going on.

I interrupted you. Please go ahead.

Dr. HANSEN. I do want to clarify just one thing specifically with regard to droughts. You heard Jerry say that he put it in a category of two to one, I believe, two out of three that we are gong to get more extensive midcontinental droughts.

My opinion is it is much more probable than that because of the kind of studies which I briefly described here, some of which have not even been published yet, and they are included to some extent as an attachment to my testimony.

But at this time it is not—it is certainly not appropriate to describe this as truth. We do not know that. But in my opinion, it is very likely that droughts will intensify at low and middle latitudes as the greenhouse warming proceeds.

And all I am saying is when we have a qualification at the beginning of the testimony that says the opinions represent our scientific conclusions and not policy and not a consensus of the scientific community, then I should be able to say what my opinions are.

Senator GORE. Well, let me just say one other thing, Dr. Hansen. That you have shown such remarkable courage in being candid under these circumstances. I just wanted to tell you that if they attempt any kind of retribution in return for candor, they will have on their hands the Congressional equivalent of World War III. This subcommittee—I think I can speak for an awful lot of my other colleagues, too—will go as far as necessary to protect your ability to say what is on your mind where scientific conclusions are concerned.

We want to try to find the truth, and the only way we have to get at it is to get the best scientists and ask them to give us their best conclusions. And we appreciate it. We will go to the mat for you, I can guarantee you that.

Dr. Mahlman, have you ever had an experience with OMB attempting to change your presentation of scientific conclusions to the Congress?

Dr. MAHLMAN. I have experienced a somewhat subdued version of a similar phenomenon.

Senator GORE. You have?

Dr. MAHLMAN. Yes. This was for testimony prepared for analogous hearing for the House Appropriations Committee on the 21st of February, and that in my organization, NOAA, the issue came down to a struggle as to whether if an individual scientist is asked to offer testimony whether he or she speaks for the agency or whether he or she speaks for him or herself.

And I got a lot of comments, not only from OMB but from other people in the agency in the name of clearance of testimony that I found objectionable and also unscientific, and I pointed out to them that if I were to adhere to these recommendations that I would have an integrated testimony which would be severely embarrassing to me in the face of my scientific colleagues and that I wished to get a clarification as to whether there is clearance of testimony by people who are outside my supervisory line or are they merely offering review of testimony which I always find valuable.

I did get review from OMB. I did receive conclusions from them and others that should have been changed in my testimony, according to their assertion that I found unacceptable, and I said that I find this unacceptable and I insist on having the right to offer my own testimony in my own words.

We in the scientific community demand the right to be wrong because if we do not have the right to be wrong, we have squelched the right to be creative.

And I made it very clear that I am speaking for myself, not for my agency nor for Commerce, nor for OMB, and that seemed to be the end of it and effectively for this testimony I did not receive similar feedback.

Senator GORE. Were these scientists in OMB?

Dr. MAHLMAN. Not to my knowledge. They are all anonymous.

Senator GORE. Dr. Hansen, were there scientists in OMB who ordered the change in your testimony?

Dr. HANSEN. I do not know them personally, so I really cannot say.

Senator GORE. These are nameless, faceless individuals with whom you are dealing, is that correct?

Dr. HANSEN. Yes.

Senator GORE. Sort of like members of the Science Politburo of the Bush administration. Well, I think this is an outrage of the first order of magnitude. I think that is evident.

This policy has got to change, and as I indicated before, we are going to pursue it. I am going to come back to some questions about the substance of the testimony. Let me recognize my colleague, Senator Wirth.

Senator WIRTH. Thank you very much again, Senator Gore. As pointed out earlier, today in Geneva, the Intergovernmental Panel on Climate Change opened its deliberations. The United States chairs the working group whose responsibility it is to try to come up with strategies as to what we ought to do.

A number of us thought that this would be a great opportunity for the United States of America to reclaim the lead in this area and urged the White House to embrace the idea of a global climate convention, and we were effectively stonewalled in doing so.

There are some people in the White House who wanted to do so. But apparently the decision was made at the highest level, not to do so, and therefore, we have gone to Geneva at this very important international meeting with no position.

On Friday in an attempt to perhaps put a little more pressure on, I introduced a resolution in the Senate to the Budget Committee Act which effectively urged the administration to change its mind. It made findings about the fact that local climate change was an important issue for a variety of reasons and urged the United States to become part of this global climate convention and to embrace it.

In the process of directing that resolution, we were again resisted significantly by the White House throughout the process saying we did not know enough, did not know enough. The resolution passed here on Thursday afternoon anyway, and I now hope that it will be used by our negotiators. I suspect it will certainly be used by members of other nations. The Senate is now on record unanimously as saying you ought to move in this direction and asking why the Administration is not doing so.

George Bush said in the campaign that he wanted to fight the greenhouse effect by the White House effect—not bad rhetoric, "fight the greenhouse effect by the White House effect."

I suspect we may be getting a little bit of a whitewash effect here today, but I think we ought to examine that. Perhaps it is the case that either the White House does not know what the scientific data is or disagrees with it. Let us give them the benefit of the doubt. They just do not know or they disagree.

So, let us examine for a minute both of those possibilities. Let me ask you, Dr. Hansen, who have been at the forefront of this for a long time: Have you ever been asked to brief Mr. Sununu or the White House staff on issues of global climate change?

Dr. HANSEN. No.

Senator WIRTH. Dr. Schneider, you have been involved in this issue probably as visibly as almost anybody in the country. Have you ever been asked to brief Mr. Sununu or other members of the White House staff on this issue?

Dr. SCHNEIDER. Not in this administration. A few in the previous.

Senator WIRTH. Dr. Mahlman, have you or people at NOAA been asked to brief Mr. Sununu or members of the White House staff on issues of global climate change?

Dr. MAHLMAN. Same answer, not in this administration, but in the previous, yes.

Senator WIRTH. Let me ask you, Dr. Hansen, have you been asked by the current OMB to brief any of their scientists or non-scientists about global climate change?

Dr. HANSEN. No.

Senator WIRTH. Have you, Dr. Schneider, been asked?

Dr. SCHNEIDER. No.

Senator WIRTH. Dr. Mahlman, have you been asked under this OMB to brief any of the scientists or staff people there?

Dr. MAHLMAN. In this OMB meaning since——

Senator WIRTH. Since January 20, 1989.

Dr. MAHLMAN. Not this one, but, again, in the last year, two different occasions at OMB.

Senator WIRTH. The current administration, do you know of anybody, Dr. Hansen, in the scientific community who has been asked to go in and brief the White House on the issue of global climate change?

Dr. HANSEN. No, I do not.

Senator WIRTH. And do you, Dr. Schneider?

Dr. SCHNEIDER. I know that during the transition after the election and before the Administration took office in January that the National Academy of Sciences prepared a briefing paper, which had very high attention levels to the seriousness of global warming and stratospheric ozone, and other problems called global change. And they were brought to the attention of that transition team. And part of the rhetoric, I think, the welcome rhetoric in Secretary Baker's remarks may very well have been based on that.

But I do not know of any actual briefing since they took office.

Senator GORE. Do you know of any, Dr. Mahlman?

Dr. MAHLMAN. No.

Senator WIRTH. Well, maybe they just do not know enough. Maybe they knew enough already beforehand and just disagree with the findings that you all have come out with. Now that is not terribly plausible, but Dr. Mahlman, maybe we can use your scale of probability and uncertainty again and examine that possibility for a minute.

Can you define for us, Dr. Hansen, who are the central opponents or contrarians to the findings and the science that you have brought before us so many times? And what are their central arguments?

Dr. HANSEN. I have really not gotten involved in trying to understand the politics of the problem.

Senator WIRTH. Who are the others in the scientific community? I mean, you read scientific journals.

Dr. HANSEN. Oh, in the scientific community. I am sorry, I misunderstood the question. You are asking about some of the reports, which have been published, say, in the last year?

Senator WIRTH. Who take the other point of view?

Dr. HANSEN. Who take the other point of view.

Well, you know the nature of science is such that whenever a new position or strong position is taken you question it. And everybody does that. And so I think it is unrealistic to expect that you are going to get unanimous agreement on exactly what the status of the knowledge is. I mean, that is very unrealistic.

I do not know that you can categorize the people who disagree in a very simple way.

Senator WIRTH. Is there a major school of thought on the other side with central arguments on the other side? Maybe that would be helpful just for the purposes of trying to understand what is the other side of the argument. Maybe the White House people and the OMB people have been convinced by the other side of the argument, by another school of scientific analysis.

And who are those people and what would their position be, Dr. Schneider?

Dr. SCHNEIDER. Ironically, the principal contrarians, if you will, having to do with the greenhouse effects, changes in the future, really are the very people who have testified here today. Many of the critics simply lift the caveats out of the papers that we or Dr. Ramanathan insisted on writing, my colleagues on the panel, and then use them as if they have discovered them in some political way to show that we are not being straight with these issues.

Indeed, all scientists try to run ranges of uncertainty tests and so forth. And probably you have heard from all of us the nature of uncertainties. We disagree over some details about how much they are, so we put these caveats in.

The group that has been most vocal among scientists in arguing about the greenhouse effect have not been arguing about the predictions in the future, they have been focusing, rather, on whether the historic record in the climate itself of the last 100 years reflects a greenhouse warming due to the 25 percent increase in CO_2 and 100 percent increase in methane, and so forth.

And that is where the principal debate is, whether the natural fluctuations in the system have been exceeded or not. And in that area I think it is perfectly legitimate to have debate. And my own personal view is that the signal has been detected in the record. I have a different probability than Jim, and each of us do. But these probabilities are our own intuition, and that other people can be entitled to be skeptical about that.

The fundamental question, however, as to the future is different from the past. Most of our confidence that the future will change is based on literally millions and millions of observations which tell us about the heat trapping properties of gases, not based so much on the performance of the planet this century.

If we insist on waiting for the planet to catch up to what we expect it to do, it is another 10 or 20 years to prove that beyond doubt.

Senator WIRTH. Mr. Chairman, you have been very generous with your time. Thank you very much.

Senator GORE. You are most welcome. And thank you for your work in this area.

Senator Robb?

Senator ROBB. Mr. Chairman, I apologize for having to go back and forth to a couple of meetings. I was not going to ask any questions, but I notice that Dr. Schneider is still here, and I am going to take this opportunity now to ask a question I was going to ask of the earlier panel, if I may.

I understand that some of the changes that you have been talking about over the course of the morning are not necessarily very gradual, but can have a fairly traumatic effect when they take place.

Has your modeling program confirmed that, or is that something that I have picked up erroneously in terms of the way these accumulated changes suddenly manifest themselves in changes in the atmosphere?

Dr. SCHNEIDER. No, you have not picked it up erroneously. What the modeling has confirmed is the possibility that there could be stresses, not that we know for certain what they would be.

One thing we already know without any climate change at all, the society and the environment is most vulnerable to extreme fluctuations in nature, such as extended heat waves. And what I and my colleagues think we are doing is we are changing the odds, leveraging up the likelihood of such extreme heat waves, and perhaps reducing the likelihood of extreme cold waves.

So in that sense, what we are doing is changing the frequency with which some of these intense events may occur. It is not that we are going to make them occur more often, but that we will crack certain thresholds, likes five days in a row above 95 degrees in Washington in July. We can calculate the odds now, it is around one in six. If you increase the temperature by 3 degrees, then it goes to something like one in two. It was like one face of a die goes to three. That is the sort of loading that we are doing.

But there is a second issue above and beyond that, which Dr. Mahlman also mentioned, which is the assumption of changing the odds on these climatic dice, if you will, that is assuming that the climate system will be essentially unchanged, just warmed. It is not at all clear that that is the case.

And, indeed, when we couple the atmosphere to oceans or we add in biota, as Dr. Woodwell pointed out, there may very well be more rapid or discontinuous-like events embedded in there that we simply do not know how to handle now or that we have no way to see: ozone hole metaphors if you will.

And some of the preliminary modeling with oceans do show us some of those surprises.

Senator ROBB. Thank you, Dr. Schneider.

Mr. Chairman, thank you. I apologize. I look forward to reviewing all of the testimony. And I am pleased to have an opportunity to hear, at least briefly, from this panel.

Senator GORE. Well, thank you very much, Senator Robb.

Just one final question, or a very brief set of questions for you, Dr. Hansen.

Last year you testified that 1988 was shaping up as the warmest year on record. Later, several others afterwards spoke up and printed statements to the effect that you were wrong about that.

Am I correct in recalling that just recently they have finally analyzed all of the temperatures from 1988 and have concluded that, in fact, you were right after all, that it was the hottest year?

Dr. HANSEN. What happened last year was, shortly after my testimony, it was realized that there was a so-called La Nina phenomena, with very rapid cooling in the tropical Pacific. And some scientists felt that this would cool the Earth down a lot, and the statement was even made, it would set back the greenhouse warming by 35 years.

Well, it did cool the Earth. And the Earth, last year turned out to be the warmest year in the East Anglia record, but just by a hair.

But I think, actually, the fact that we had a very strong La Nina, the strongest one in a couple of decades, and we still had a very warm year, is evidence that, in fact, there is something else going on besides natural variations.

Senator GORE. Now, could the surge in CO_2, that Dr. Woodwell told us about, be related to that La Nina effect?

Dr. HANSEN. It could well be. And that is one of the suspicions. The other one is the one that George mentioned, that the biota on the land may be involved. But it could also be that the warmer ocean temperatures release more CO_2.

Senator GORE. Now, secondly, one of the challenges to your testimony of last year came from someone at NOAA who said that the 100 year temperature record of the continental United States indicates that there has been no warming in the last century in the United States.

Now, my response to that was, since the lower 48 represents only 1.5 percent of the Earth's surface, it is unlikely that a global trend of this sort would be always and everywhere visible in each 1 or 1.5 percent section of the Earth's surface.

But I understand that other data now at NOAA indicates that, in fact, the initial conclusion about that 1.5 percent of the Earth's surface may not have been correct. Can you shed some light on that?

Dr. HANSEN. Well, if you look at the attachment to my testimony, there, in fact, is a section that does include a discussion of that and some graphs.

There is available a data set, which Tom Carl of NOAA has spent several years constructing. It is called the Historical Climatology Network. And it is agreed, I believe, by all the scientists involved, by far the best data set for the United States. It has been corrected for station moves, for urban effects and for instrument changes.

That data set shows a warming trend of .26 degrees centigrade per century.

We also show in that section that if you add in Alaska and Hawaii, since we do not really have a prejudice against the other two states, then the warming trend in the United States is .33 degrees centigrade per century.

So it is not that much different than the rest of the world, which is about half a degree centigrade.

So I think if that data set had been used initially, there probably would not have been a story.

Senator GORE. So the original story was sort of an infrared herring. I am sorry, I am going to give the blame for that one to Dr. Schneider.

Dr. SCHNEIDER. I was hoping you would not remind them.

Senator GORE. All right. I do not understand why NOAA did not use the best data set that was available.

Dr. HANSEN. Well, you should also give NOAA credit for constructing the best data set.

Senator GORE. All right, I will.

Did you want to comment briefly?

Dr. MAHLMAN. Yes, I would like to comment on that myself. I think that it is very easy to get obsessive about the nuances of a particular analysis of a particular data, but I cannot help but avoid the assertion that the data was never assembled from the perspective of trying to put together a climate monitoring data set.

And the legion of corrections that are required for this data set is an exercise in creativity and scientific intuition, which cannot be underestimated. But my real concern, and the reason for speaking up is that I do not see a whole lot of evidence that we are preparing for the next 100 years in our climate date measurement and monitoring system. And I think that is one that we need to have serious international attention about.

Senator GORE. Well, this committee agrees with you. And Chairman Hollings has been particularly active on that specific point there, too.

And I want to conclude this hearing by expressing my thanks to all of the witnesses who have come. As I will reiterate a third time, we appreciate the courage that is not always required, but was in this case, to come forward with the best presentation of the evidence in science possible.

We intend to pursue this. I intend to ask for the nameless, faceless individuals at OMB, who censored this testimony, to come and explain what scientific basis they had for substituting their conclusions for those of the atmospheric scientists.

So we intend to pursue every aspect of this in some detail.

With that, this hearing will stand adjourned.

[Whereupon, at 12:45 p.m., the hearing was adjourned.]

O