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CLIMATE CHANGE: THE STATE OF THE SCIENCE

HEARING

BEFORE THE

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HOUSE OF REPRESENTATIVES

ONE HUNDRED SEVENTH CONGRESS

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CLIMATE CHANGE: THE STATE OF THE SCIENCE

WEDNESDAY, MARCH 14, 2001

House of Representatives,
Committee on Science,
Washington, DC.

The Committee met, pursuant to call, at 10:10 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Sherwood L. Boehlert (Chairman of the Committee) presiding.

Committee on Science
U.S. House of Representatives
Washington, DC 20515

Hearing on

Climate Change: The State of the Science

Wednesday, March 14, 2001

Witness List

Dr. Daniel L. Albritton
Director, Aeronomy Lab,
National Oceanic and Atmospheric Administration

Dr. Charles Kennel
Chairman, Committee on Global Change Research,
National Research Council

Dr. Berrien Moore
Director, Institute for the Study of
Earth, Oceans, and Space
University of New Hampshire

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HEARING CHARTER

Climate Change: The State of the Science

Wednesday, March 14, 2001

1. PURPOSE

The purpose of this hearing is to examine: (1) the state of our understanding of climate science, (2) the gaps in our understanding that limit our ability to detect, attribute, and predict climate change, and (3) the adequacy of the federal government's approach to filling these gaps.

Testifying before the Committee are three witnesses: (1) Dr. Daniel L. Albritton, Director, Aeronomy Lab, National Oceanic and Atmospheric Administration, (2) Dr.

Berrien Moore, Director, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, and (3) Dr. Charles Kennel, Director, Scripps Institution of Oceanography.

2. THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

In 1990, the House Science Committee passed the National Global Change Research Act, which later became law and created the U.S. Global Change Research Program (USGCRP), a multi-agency program coordinated through the President's National Science and Technology Council to focus U.S. research efforts on climate change and other global environmental changes, such as deforestation and ozone depletion.

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Agencies participating in the program include the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), the Department of Agriculture (USDA), the Department of Interior, and the Environmental Protection Agency (EPA). Total funding for the program for the last two years averaged about $1.67 billion.

The program funds research by both government and non-government researchers, and has the following goals:

To observe and document changes in the Earth system

To understand why these changes are occurring

To improve predictions of future global changes

To analyze the environmental, socioeconomic, and health consequences of global change

To support state-of-the-science assessments of global environmental change issues.

The USGCRP has achieved "an impressive array of scientific accomplishments," according to a 1998 report by the National Academy of Sciences (NAS). It has helped predict the 1997–1998 El Niño weather phenomena, improved our understanding of stratospheric ozone loss, helped decipher ice cores providing evidence of past changes in the Earth's environment, helped develop large-scale climate models, and helped us better understand how terrestrial and marine ecosystems affect the carbon cycle.

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However, the NAS also criticized the program. In the 1998 report entitled *Global Environmental Change: Research Pathways for the Next Decade,* the Academy leveled several criticisms at the program and recommended improvements. For example, the report criticized the under-funding of critical research priorities for which the program was created, blaming the lack of coordination between agencies participating in the USGCRP and too heavy an emphasis on expensive space-based observational systems. It also faulted the program for failing to make a serious commitment to maintaining the long-term continuity of climate data-collection systems, which are critical to understanding changes in the climate over time.

The Academy report urged the USGCRP to take a new approach with a more sharply focused scientific strategy. Specifically the Academy urged the USGCRP to, among other things:

Secure more powerful computers needed to run the larger, more complex and more useful models currently under development. The Academy emphasized that the U.S. is no longer the leader in this critical field.

Tie its decisions regarding what research to fund and what kinds of observation systems to build more closely to answering a list compiled by the report of over 200 "unanswered scientific questions" in six major areas of global change research.

Shift funds from larger, space-based observing systems to more agile and responsive systems, taking advantage of recent technological advances in small satellite systems, robotics and microelectronics.

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3. THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

In 1988, the Intergovernmental Panel on Climate Change (IPCC), composed of hundreds of scientists from more than 50 countries, assembled to conduct periodic assessments on climate change and its consequences. To date, the IPCC has released three major reports describing the climate system, the extent to which the climate has changed, and projections of future change. The IPCC issued its third assessment earlier this year.

Among the most recent report's findings were that the levels of greenhouse gases in the atmosphere have risen, the temperature of the Earth's surface has grown warmer, sea level has risen and the oceans have also warmed, and some aspects of climate, such as global precipitation patterns, have changed. The IPCC based these findings both on direct observations of climate data and on such indirect observations of temperature as tree rings, corals, and ice cores.

The IPCC also concluded that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." The IPCC based this conclusion partly on results from global climate models and partly on the unique nature of the recent temperature rise when compared with new data showing that the climate has been relatively stable extending as far back as the past 1000 years.

Finally, the IPCC projected that in the future greenhouse gases would continue to rise, accompanied by additional warming, sea level rise, and climate change. The group projected that by the end of 2100 the global average temperature of the Earth could rise by 1.5 to 5.8 degrees Celsius.

The IPCC's "Summary for Policymakers" is attached.

4. THE RESPONSE TO THE IPCC

Some have criticized the IPCC, charging that its "Summary for Policymakers" does not accurately reflect the underlying scientific report, having selectively left out information that undercuts the group's more worrisome climate predictions.

Some disagree that climate change can be attributed to human activities at all, citing the many areas of uncertainty that remain important research topics—such as the response of the oceans to rising temperatures, the effect of aerosols on cloud formation, and the feedback relationship between the climate and the biogeochemical cycles, such as the carbon and water cycles.

Others have criticized the IPCC's reliance on computer simulations to forecast possible future climates and its use of so-called proxy data, such as tree rings, to give an accurate reflection of the temperature of past climates.

Still others have disputed IPCC's finding that the temperature of the Earth has increased, pointing to satellite records collected since 1979 that show, if anything, a much smaller warming pattern.(see footnote 1)

5. QUESTIONS TO THE WITNESSES

Witnesses were asked to address the following questions (not every one was posed to each witness):

What evidence do we have that the Earth's climate is changing, and how reliable is that evidence?

To what degree is climate change attributable to anthropogenic activities, what evidence supports this assertion, and how reliable is that evidence?

What factors limit our ability to detect, attribute, and understand current climate change and to project what future climate change may be?

How should the government prioritize its efforts to overcome these limiting factors, and what steps should the government take to overcome them?

What are the most important areas of climate science in which we must improve our understanding in order to detect and attribute climate change?

Is federally funded research adequately focused on those areas, and what steps should the government take to better prioritize research efforts among the climate sciences?

Climate Change: The State of the Science

Chairman **BOEHLERT.** It is a pleasure to welcome everyone here for the third of our three opening hearings on the Committee's priorities for the 107th Congress—education, energy, and the environment. The subject of today's hearing is the environment, and specifically, global climate change. I think it is safe to say that this is the most controversial of our three opening topics. But there is one principle concerning global climate change on which just about everyone can agree, and that is that we need a strong and continuing research program to understand more about climate. And it is that research program that is our primary focus this morning.

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Our witnesses, in particular, Dr. Albritton, will review the current state of the science. But all our witnesses have been asked to highlight the gaps in our knowledge of climate change and what we might do to fill them. This Committee created the U.S. Global Climate Change Research Program, which is due for an evaluation and, perhaps, some additional legislating.

Today's hearing will help us assess whether the Federal Government's research program needs to be restructured and/or redirected and whether funding is adequate. Obviously, the science of climate change has policy implications. I wish that the Administration would have waited to hear from experts like the ones we have before us today before embarking on what I believe is a misguided and unjustified reversal of position.

But policy is not what we are focusing on at today's hearing. We will have additional hearings at both Subcommittee and Full Committee on the policy implications and on the science itself. So I urge my colleagues to focus today on the state of the science of climate change and, especially, on the future research agenda for understanding climate change.

What are the outstanding gaps in our knowledge base? How and when might we get answers to those questions? These issues have not been the subject of many recent hearings. So I look forward to an open and vigorous, and rigorous, conversation about those matters—one that I hope does not simply rehearse previous discussions of this issue.

And let me say that I have been getting a little bit better each week at controlling the time, and I will be holding the witnesses and the Members and the Chair to their 5-minute allotment.

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Mr. **HALL.** Mr. Chairman, thank you. My time is not up yet, is it? I want to thank you, Mr. Chairman, knowing your sincerity in this and, of course, once again thank you for your openness and your cooperation to this side of the podium. We appreciate it. Climate change is a thorny topic and you and I are probably poles apart on the global warming thrust. And I admire our President for clarifying his position on it. And I am anxious to hear these three gentlemen today.

And I think ensuring that our limited research dollars are spent wisely is very important to us. And I think it is also important that we have the other major players participate with our own taxpayers in the expenditure, the vast amount of dollars it will take to satisfy the quest of some for global warming. I think a sign to reduce carbon dioxide in power plants is a good thing. I want to—I look forward to hearing these experts. And I am not going to take any more time, except to tell you that I have some real doubts about the overall thrust, the overall cost.

And when we talk about restructuring or redirecting, why, there might come a time when we think about retiring the thrust because I just don't think that we are able to do it. I don't think we can go it alone and I don't think we can go it without China, Russia, Mexico, India, and you name all the others. I think you would be foolish to.

And I think it was a waste of time to send all those people to Tokyo. I think 1,200 people went over there at the end of the day when the House and Senate had both indicated that they were not supportive. Until we get to be supportive in a joint thrust, and we are in a good time to cure items like that, because of the surplus we have—and if the Chairman, in his leadership, leads us in that direction, I would say to him, it is a good time because we do have money to do some of the things that, perhaps, we ought to do. And I am still—obvious that I have an open mind. At this time, would yield 1 minute to the gentlelady from Texas, Ms. Johnson.

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Ms. **JOHNSON.** Thank you, very much, Mr. Hall. And thank you for the opportunity to speak today on global climate change, an issue I take very seriously. You can hear it in my voice this morning. Last November, I attended the UN Framework Convention on Climate Change, COP–6 at the Hague in the Netherlands. There were many technical issues discussed there, including credits for carbon sinks, how to deal with countries that do not meet emission reduction goals, how developing countries obtain the financial resources necessary to deal with the adverse effects of climate change.

The last point was very important to me. While the focus of today's hearing is on the science of climate change, we must remember the human dimension of climate change, those who stand to gain and lose the most from changes in global weather patterns. Just recently, I heard a researcher talk about even the spread of the viruses, Ebola virus, HIV, whatever, is very affected by the climate. And while it is going to be very, very expensive, and we must use common sense, we have no choice but to attempt to do something to move in that direction. We got our message very loudly and clearly at this convention. Thank you very much and I will put the rest of my statement in the record.

Mr. **HALL.** I thank you very much. And if we have about a minute left, Mr. Chairman—

Chairman **BOEHLERT.** A minute and 8 seconds. Thank you.

Mr. **HALL.** —to yield it to the gentlelady from California, Ms. Woolsey.

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Ms. **WOOLSEY.** Thank you very much, Mr. Hall. Thank you, Mr. Chairman. Two weeks ago, this Committee had a hearing on energy and the Panel briefly touched on climate change when they spoke about the effects and implications of our Nation's reliance on fossil fuels. I was particularly encouraged by the remarks on this subject because they were nonpartisan. They were scientists. They were witnesses basing their comments on scientific understanding. I commend the Chairman for holding the hearing because we all need to learn about the science behind climate change.

And at the heart of the change, science has a well-established theory, the greenhouse effect, that states that carbon dioxide emissions, a heat-trapping gas that is produced by the burning of fossil fuels, significantly contributes to the global warming trend. We have to hear more about you—from you about that because we must develop clean fuel technologies. Thank you, Mr. Chairman.

Mr. **HALL.** Mr. Chairman, I yield back my time. I wanted enough time to let Mr. Udall from Colorado introduce Mr. Albritton, but I know you will do a good job of that.

Chairman **BOEHLERT.** Okay. Fine. Thank you very much. And let me stress that we are going to keep to the 5-minute time limit, and we would greatly appreciate the witnesses who are testifying doing the same thing. Try to summarize your statement. Let me stress at the outset that we are not here to debate Kyoto. We are not here to debate policy. We are here to look at science and the gaps in the science space to help us all better understand this issue. With that, let me also say that the record will remain open for any other Members who wish to have a statement in the record.

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Our first and only Panel for today consists of Dr. Daniel Albritton, Director, the Aeronomy Lab, National Oceanographic and Atmospheric Administration; Dr. Berrien Moore, Director, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire; and Dr. Charles Kennel, Chairman, Committee on Global Change Research, National Research Council. Gentlemen, thank you all for serving as valued resources for this Committee, and we look forward to your testimony. Dr. Albritton.

STATEMENT OF DR. DANIEL L. ALBRITTON, DIRECTOR, AERONOMY LAB, NATIONAL OCEANOGRAPHIC AND ATMOSPHERIC ADMINISTRATION

Dr. **ALBRITTON.** Thank you, Mr. Chairman. It is a real pleasure to be before your Committee. It is a real pleasure to be before your Committee to summarize what we do know and what we don't know about an issue as complex as climate change and its relation to humankind. I will be pulling the summary points from the recent report of the Intergovernmental Panel on Climate Change. And in order to meet your 5-minute time limit, I have prepared a few talking points on overheads, and I believe copies of those overheads are at each of the members' desks.(see footnote 2)

Before I note what I think are the three major new findings over the last 5 years of research, let me state a few points about the science of the greenhouse effect that fall into a phrase, I think, a local phrase, science holds these self-evident, and that is, with very, very high certainty, science can make two statements. Number one, there is a natural greenhouse effect. It is a built-in part of the job description of the planet and it has always been there. The greenhouse effect keeps our planet warmer than it would be otherwise. It operates from trace gases like water, CO, and methane, which have been part of the atmosphere as long as there has been an atmosphere.

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So why is the term greenhouse effect often cited as an issue? And that is the second point. It is also very, very clear from impeccable measurements that the amount of greenhouse gases in the atmosphere is increasing and that the causes of those increases are largely human activities. CO has increased about 30 percent over the industrial era. Methane, a second greenhouse gas, has doubled over that time period. We know from basic physics that those gases are trapping more and more heat as their abundances increase.

The key question is not whether there is a greenhouse effect. It is not whether we are altering the greenhouse effect. The key question in the issue of global warming is, indeed, what are the consequences of our changing it?

And today, I wanted to bring to you three new findings from the scientific community. These are embodied in the recent report, of which you have a copy of the summary, of the Intergovernmental Panel on Climate Change. Several hundred of the worldwide scientists and program managers took 3 years to prepare this updated statement. There had been such a statement in 1995. There had been a second such statement in—in 1990, a second in 1995. And so this is the third statement of understanding of the climate system.

On the three points that I will report, I have tried to arrange them into a point that we have the highest confidence in and then going to points that we have less confidence and that we wish we knew more about. So let me comment on the very first finding of the new report. It is on the second page and the second overhead of this summary.

Point number one, there is a collective growing picture of observations of a warming world over the past century. And, as you note on the handout and on my overheads, I have tried to sketch some indicator visually of the confidence that the science community has in this statement. But more importantly, beneath the statement, are a graph and a few extra supporting points that show why we have that confidence.

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Global temperatures undoubtedly have increased about .4 to .8 degrees centigrade. That is about .7 to 1b degrees Fahrenheit over the past 100 years. And the reason that can be stated with certainty is two-fold. This figure shows a new data set gained over the last 5 years of surface temperatures in the northern hemisphere for the past 1,000 years. The earlier data are from ice cores and tree rings and other historical measurements. And that departure from the average is shown in blue. On the right-hand side of that plot are the measurements made in the last 150 years with actual thermometers taking the temperature of the earth.

Two points—you can see that those two methods, the indirect from corals and tree rings, and the direct from thermometers, overlap for the 100-year period where the two data sets exist. Second point, these direct observations show that the last 150 years have been remarkably different than the previous 850 years.

There are other things that indicate the world is warmer. Glaciers are retreating. The only exceptions are near sea level, where rainfall has increased. The amount of snow cover each year, while it varies, on the long term, is decreasing, and average sea level has increased about 1/10 to 2/10 of a meter reflecting the fact that water expands when it is warmer.

So here are a whole host of direct observations that are consistent with the world getting warmer. The question is, of course, is this a natural variation, or is this something that involves greenhouse gases?

And that brings me to the second point from the world scientific community. And that point is this. There are new and stronger evidence that most of that observed warming over the past 50 years is due to human activities. And the evidence for that, stated with a little less confidence than the direct observations—the evidence are in those two plots. This is a 150-year temperature record shown in red, and the gray band is what climate models get trying to simulate that temperature record.

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The left-hand figure is what climate models will yield if that change were due only to natural variation. The right-hand figure is the simulation that would occur if greenhouse gases are included. And, as you can see, the fit of the last 100 years, with the natural and the climate greenhouse gas inclusion, matches the observed record much better. That has been aided by 5 years of data and it has that 1,000-year temperature record for context.

The last question relates to the final point. What could these observations and what could these—this understanding portend for the future? And this is a more difficult thing to state. And that is to forecast is much more difficult than to observe. But here is the voice of this world scientific community. A continued growth in greenhouse gases is projected to lead to very significant increases in global temperatures and global sea level. That statement is based on a set of plausible future scenarios of economics, technology, population growth, taking the high and the low ends of all of those ranges.

And, as you can see, the extremes of that uncertainty, range as high as 5b degrees Celsius increase in 100 years, down to 1b degrees Celsius increase by 100 years. If that were to occur anywhere in that range, that would be larger than any of the natural variations over the last 10,000 years.

There are things that are tough to predict and to forecast. State of the science is unfortunately lacking to predict tomorrow's climate, next year's climate, the climate in a particular state, but it can say certain things, that land areas, like our own, will warm faster than the global average or oceans. And, secondly, and most importantly, that weather is apt to be much more variable in a warmer world. And that is, more frequent extremes, more variable, more part of the planet that looks more tropical, as we know it.

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Finally, let me close, Mr. Chairman, having given three new updated science statements, but I want to underscore one science point that has persisted through decades of understanding of the greenhouse effect. And this is my last point on my last sheet. Everything that we know points to the fact that if a greenhouse warming occurs, it would be very, very slow to reverse. And that arises for two reasons—the lifetime of CO in the atmosphere outlives us. And that is, several hundred years after we place CO in the atmosphere, 25 percent of it would still be there, still trapping heat and adding to the warming. Secondly, the oceans are big and sluggish. They will be slow to warm up. They would be very slow to warm off—to cool down.

So I have commented on observations. I have commented on updated diagnostics. I have commented on new projections. The assessment done by the scientists in the IPCC is to provide an improved statement that would be a scientific input to this complex social, economic, technical equity issue that we know as global change. If I have glossed over any points in trying to meet the time schedule, please do—and I would be happy to entertain questions. Please ask them. Thank you very much for your interest in the update.

Chairman **BOEHLERT.** We are going to pause.

STATEMENT OF DR. BERRIEN MOORE, DIRECTOR, INSTITUTE FOR THE STUDY OF EARTH, OCEANS, AND SPACE, UNIVERSITY OF NEW HAMPSHIRE

Dr. **MOORE.** Is this better? I am going to take as given that the increases of carbon dioxide and other greenhouse gases pose today, and will continue to pose in the future, serious scientific and policy issues. Given that, I then ask what are the key scientific challenges before us? What steps do we need to take with respect to our scientific agenda?

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First, I think we must arrest the decline of the observational network throughout the world. This decline is acute in regions like Africa, Russia, and parts of South America, but it is not restricted to those regions.

Second, we must sustain and expand the observational foundation for climate studies. We must seek to obtain climate-relevant data. This means long-term commitments to observations. For instance, the monitoring of carbon dioxide, both in situ and, perhaps, from space, the in situ monitoring of the world's oceans.

Third, we must understand mechanisms and factors that lead to changes in the radiative forcing of the atmosphere. We must be able to turn emissions into concentrations in a more accurate fashion. This ties back to observations. What are the observations that we need to better tie emissions to concentrations?

Fourth, we must understand and characterize better the unresolved physical and biological and chemical processes. For instance, the role of clouds. This has been challenging to us for a decade and longer. It remains challenging. What will the role of clouds be in a future earth? Arctic Sea Ice—we see a thinning of the summertime Arctic Sea Ice. Can we explain that phenomena? Is it part of natural variability or is it a part of an anthropogenically changed climate? What is the macrocirculation of the ocean and how might it change?

Fifth, we must address more completely long-term climate variability. We are attempting to see a signal and the noise is climate variability. And, therefore, we must understand climate variability better. But there is also a benefit. By simply understanding the variability of climate, we will be better posed to address not only climate change, but the natural challenges that climate faces us with.

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Sixth, we must explore in our calculations directly the probabilistic nature of climate. Climate system is complex. It is somewhat chaotic. It has unresolved features. The only way that we begin to actually build confidence in our projections is to have done many of them. We need to understand the statistical character of climate.

And that poses the next problem. We must expand significantly the available computing resources to attack this problem. The lack of available computing resources hinders the scientific effort, and that is particularly true in the United States.

Eight, we must improve the connection between regional climate and the global studies. Humans are affected at regional scales, not at the global scale.

Finally, the last two. We must link better the physical, biological, chemical system with the human system. We are, after all, talking about ourselves.

And, finally, climate variability and climate change—this is truly an international issue, and, therefore, we need to strengthen the international scientific agenda as we go forward. Thank you very much, Mr. Chairman.

Chairman **BOEHLERT.** And now, the third panelist in our only Panel for the day of distinguished witnesses, Dr. Kennel.

STATEMENT OF DR. CHARLES KENNEL, CHAIRMAN, COMMITTEE ON GLOBAL CHANGE RESEARCH, NATIONAL RESEARCH COUNCIL

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Dr. **KENNEL.** I have—there we are. Thank you very much, Mr. Boehlert. It is a pleasure to be here. I would like to concentrate my testimony on the results of the recent report that the Committee on Global Change Research generated. And it focuses on how to organize the research agenda that was just outlined by Dr. Moore. So we are going to talk about some of the organizational issues.

Before I do that, I would like to leave you with a few rather general points from that report. Climate scientists have to study the world at a global scale. They have to study the ice, the oceans, the atmosphere, the land, the living things on the land, in order to understand what will happen with a global climate. But it is absolutely essential to embark upon a program in which we increasingly focus on regions, first, at the continental scale and—as for the El Niño, and then at the national scale; finally, on the regional scale, so that we can finally get down to helping answer what is the most important question in all of environmental science. What does it all mean to me?

Next viewgraph, please. Now, climate scientists talk about abstract things, like the global average temperature having increased by .4 to .8 degrees centigrade. And that is a wonderful concept. It helps us understand the system, but it doesn't really help people understand the implications. One of the things that they are concerned with, for example, will there be an increase in the number and severity of severe weather events?

We would like very much to be able to better predict these. But in order to predict these, in addition to the information and understanding that comes from global climate studies, we need to fold in understanding about what is happening on the ground, what is happening with the human systems, what the rivers are like, what has happened with forest management practices, and so on, and so forth.

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And so in order to make global change research meaningful, we now need to embark upon a program of regionalizing it, of extracting its meaning for every region and every sector of the economy.

In certain areas—next viewgraph, please—we have actually embarked upon a program of doing this. One of the key accomplishments of the U.S. Global Change Research Program, over the last ten or so years, has been an increasing ability to forecast the climate 6 to 9 months ahead. Now, this is a so-called El Niño forecast, and it is already getting sufficiently good to attract the attention of the agricultural commodities market.

And so now we are beginning to understand when and where there will be increased rainfall in the United States as a result of conditions in the far distant western Pacific. And right now, one of the frontiers of this subject—there are scientists in California and New York translating these predictions for rainfall into actual predictions for what will happen in the watersheds of California and other major basins around the world. Now, and that will help electricity managers, for example, in California, understand what next year's stream flow may be.

Now, of course, the investment decisions that they need to make on infrastructure take place over—they have to think in the 10-, 20-, 30-year time scale, which is the same time scale on which we expect things like global warming and longer climatic cycles, things with arcane names, like the Pacific Decadal Oscillation, and so on. We expect these longer climate cycles to interact with the accumulation of greenhouse gases to produce the climate 10, 20, 30 years ahead. Can we make useful predictions that will be useful for decision-making on that scale, and should people pay attention to them? That is the question.

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One of the things that we have learned from our experience with studying the global climate and also the El Niño, has been that we now understand—next viewgraph—that we need to take a system approach to the development of understanding of climate in general. We need to start, as Dr. Moore emphasized, with global and regional observing networks. They need to be placed into context by large scale computer modeling and simulation. When that context is completed, then we need to understand the impact of these predictions on the regions and on the sectors of the economy. And we need to assess those impacts very carefully, both for their scientific uncertainty and for understanding who it will be that will be affected.

And, finally, the goal should be—in developing environmental information systems, the goal should be to develop an end-to-end system that can improve decision-making in the environmental area. We believe that much of our experience is drawn from the climate area, but we believe that systems like this pertain throughout the region, throughout the environmental enterprise.

And a final point I would like to make is that the same system that helps extract economic value from environmental information is also the one that creates a platform on which good policy can be made. They are related.

Now, what is it that needs to be done to accomplish this creation to create an end-to-end system like this? Next viewgraph. Our committee has concluded that a new management philosophy is needed, a national framework that will sustain and integrate the webs of observing systems that we need, that will attend to expanding computation and modeling capacity and apply it to the problems of interest, and would initiate the regionally focused environmental research and assessment, and finally to create the partnerships, the working—true working relationships, not only between the physical and the social scientists, but also the public and private decision-makers and the scientists, and connect them up nationally and regionally.

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So that is obviously a very long-term program. What is the first step? Our committee recommended—next viewgraph and final—our committee recommended establishing a high-level governmental authority. We are not the architects of government, but we suggested that you create one. And that its essential characteristic be that there are resources—a line item with resources accountable to OMB and to you for the interagency and the national and regional coordination that is required to start building an end-to-end decision-support system.

Chairman **BOEHLERT.** Thank you very—excuse me—thank you very much. And I am not surprised, with the credentials and background and expertise of our three panelists, that you touched on a number of areas, and your more detailed statement, which is part of the permanent record, is even more comprehensive. But we need help.

And I would ask that each of you try to identify the three things, with some specificity, that we need to do first. I mean, you know, new management policy. I think we can say there is so many areas of government that need a new management policy. National framework for action, well, that is something we can all subscribe to. And creation of partnerships are so very valuable, but can we get to some specifics?

And let me ask, starting with Dr. Albritton, the three panelists to respond to that question. Something—and try, as much as possible—I know this is the august Science Committee, but in plain English, if you can guide us. What are the three things you would recommend that we consider doing to fill the information and knowledge gap so that all of us, no matter how we perceive the issue, will have a better base upon which to continue our observations?

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Dr. **ALBRITTON.** Thank you. Could I phrase that as what are my three wishes? And I will do this in the terms of research and science and I will do it—I will present my three dreams in the context of, perhaps, in a few future years, having a better understanding of how the planet works so that that information can be brought to groups like this that would help this complex decision associated with global change.

My first dream or my first wish would be to better understand two aspects of climate forcing, that is, things that cause climate to change that relate to us. The first one is to understand how carbon storage works so that we look not only at CO as a gas in the atmosphere, but in its full manifest cycle through the planet. And the second part of that first wish is a better understanding of the shorter-lived greenhouse gases that we already are focusing and considering for regional pollution. These are things like smog, ozone. They are fine particles in aerosols. And I suspect that if we have better information on those, we will find that we may be getting bigger bang for the buck in multiple issues, as opposed to one issue.

The second dream I would have is better understanding of water-related processes in the atmosphere. That is, water vapor, clouds, precipitation, because it is those that relate to the extremes of the climate system.

The third wish would be to be smarter on regional foci, as has been indicated. And that is, be able to come to you and say, our forecast for region "X" is such and such. And to be able to do that, it takes the information home to people who make local decision-making. To be specific, that relates to better computing power and, secondly, a better understanding of the multiple environmental issues in that region. For example, what impact will climate change have on struggles with air quality in that region? Those would be my three wishes.

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Dr. **MOORE.** Well, I guess my first wish would be to have the—Dan Albritton's three wishes because I found myself very much in agreement with him. On the carbon storage, I am in very strong agreement, and I would just simply add, we need to understand the sources and sinks, the places carbon comes from and where it goes, and how that might change in the future.

Secondly, I would like to believe that we have the political and scientific muscle to tie weather observations to climate. That we are willing to make climate-relevant measurements with our weather-monitoring system. That poses serious questions of calibration and so forth. Things that cost money.

Thirdly, we must have the computing resources to conduct the studies that are needed. We must have the computing resources to conduct the climate simulation studies that are needed. This is particularly true when we try to analyze questions like extreme events or questions at regional scale. These are complex issues and they require significant computing power.

Chairman **BOEHLERT.** Dr. Kennel.

Dr. **KENNEL.** My committee has three wishes. Number one, build observing systems for the environment. Make them comprehensive. Sustain the ones we have got, connect the ones we have got into a more information meaningful way. In specifics, for example, for the ocean, try to assure uniform global coverage of ocean circulation, temperature, and chemistry. It is a difficult problem and we are embarking on a program called Argo that will attempt to do that. But there are serious problems, for example, with coverage in the southern hemisphere and in the Antarctic southern ocean where much of the retirement of carbon dioxide takes place in the ocean. Another one would be to start measuring, on a regionally differentiated way, how air pollution is beginning to interact with regional climate.

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Second—this has been said three times—increase the computational capacity available to environmental science. And, third—this has been repeated twice—get started on regional programs that interconnect different environmental issues and relate them to global climate change.

Chairman **BOEHLERT.** Thank you very much. My time has expired. We will probably have a round two because I would like to go even beyond that and get a little more specific. Mr. Hall.

Mr. **HALL.** Mr. Chairman, I yield to the gentlelady and I will take my shot at it on the second round.

Chairman **BOEHLERT.** All right. Ms. Woolsey is recognized.

Ms. **WOOLSEY.** Well, thank you, Mr. Hall. I traveled to the Antarctica with the National Science Foundation. Talk about a learning experience and about global warming. But at McMurdo Station I asked the scientists, particularly when we first got there, their opinion on global warming. I was amazed at how silent they were and I became very convinced that their silence was based on the fact that they had to be absolutely 100 percent sure before they could speak out. And my fear is, by then, it will be too late. So I thank you for today.

I want to add a fourth wish, Mr. Chairman, and I would like each of you to speak to this. And that is, that we find a way to speak about global warming in plain English because people get it emotionally, but they aren't able—aren't always able to compute it and put it in their language and so they can speak about it and support our science. So what would you do so that people would understand why becoming more tropical is not what they should—that they absolutely should be concerned about it? How are we going to talk about it in plain English, starting with you, doctor? Well, you are all doctors.

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Dr. **ALBRITTON.** Thank you. You have put your finger on probably one of the more difficult aspects of any complex problem of the environment, and that is, how to relate it in the terms of the ultimate policy-maker, which is the citizen and the voter, exactly.

Three things, I think, would help there. First, put more effort interacting with the educational system. The reason I say that is that is planting seeds of understanding and it is amplifying through the students, through the households involved, what the issue is, what it is all about, and it is that long-term investment for the future that education has.

The second point, there are many scientists who want to seek that interaction with the public as a part of their jobs. And I believe that as laboratories, agencies, institutions to explicitly support the development of that technique among our scientific community within the universities, within the national labs, ought to be a national duty.

Now, the third is that I believe we have weather information transmitting systems, commercial channels, weather forecasters—climate is an aggregation of weather. It has always struck me that that group, technically trained, but very skilled at getting to the point and stating the bottom line, making it user-friendly, putting it in a decision-relating framework about tomorrow, that that would be a group that we could very actively partner with to put a sidebar climate message on weather. Trial cases were done for that with the recent strong El Niño and I thought it was highly successful.

Dr. **MOORE.** I think this is a very important question and I would direct it at myself and my peers. And that is, we need to be clearer about what we know, what we think we know, and what we don't know. Unfortunately, I find that myself and my peers and then, consequently, others, confuse what we know with what we think we know and what we don't know.

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Dr. **KENNEL.** I would support all of that and just simply add that if we can do a better job, showing real understanding on a region-by-region, place-by-place basis of what people's problems are, and how they may affect them, and if they see through shorter-term forecasts, like the El Niño forecast, that things actually work out, then we may build some confidence for the longer term. But surely, we have to learn how to both do the science and explain the science in terms that are meaningful at the local level.

Ms. **WOOLSEY.** Thank you, very much.

Chairman **BOEHLERT.** Thank you very much. There, now, I have got it. Everyone gets one wish now. This is the Woolsey Doctrine. And my wish is that we focus on filling the knowledge gap to find out what we don't know and to get recommendations as to how we proceed to fill in those knowledge gaps so that we can deal with our—either confirm or alter our preconceived notions. This town—everyone in this town likes to say they are for science-based decision-making. But my experience is, until the science produces something that is politically inconvenient, then they look to another avenue to travel down. The Chair is pleased to recognize a distinguished scientist, in his own right, Dr. Vernon Ehlers.

Mr. **EHLERS.** Thank you, Mr. Chairman. And my only wish is that everyone would simply agree with me so we could get on with things. Having said that, I want to follow along the line of the questioning of Congresswoman Woolsey, but in a different sense. There is also some disagreement in the scientific community, and I am not sure, at this point, to what extent there is disagreement. But Dr. Kennel, for example, one of your predecessors, who is a dear friend of mine at Scripps, Bill Nierenberg, was—agreed very—disagreed very strongly with some of the conclusions here. How many scientists are still questioning that and what is the basis on which they are questioning what we have heard here today? And are they pursuing research to demonstrate that you are wrong? Do they have scientific reasons for their opposition? I am trying to get a handle on that as a scientist. Dr. Kennel, I will ask—give you a chance first.

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Dr. **KENNEL.** Well, as you well know, the scientific community itself contains a whole variety of—until the issues are settled, there are a wide variety of views and they are tested through the literature and through conferences and measurements and computations, and their arguments are carried out in the literature. And every scientific community has, as very useful members, the skeptics who do not believe the current-received wisdom and they are constantly pointing out holes in your knowledge. That is their job. And the scientific edifice is improved by the system—

Mr. **EHLERS.** I understand that. But I am just wondering, are they still out there? Are the diminishing? Are they—

Dr. **KENNEL.** Oh. Yes. There are skeptics. But then the question, for the policy arena, is how to construct a process that characterizes the views of the general community and also the spread of those views? And this is why, for example, the climate community went to the assessment process, as now personified by the Intergovernmental Panel on Climate Change. And this contains hundreds of scientists from different countries, backgrounds, funding sources, presumably intellectual biases, and they work together to try to craft common positions on issues of policy interest, and, at the same time, to characterize the spread and uncertainty and understanding so that policy-makers may also assess that. And it is with—and they try to set a context in which you can view the views of the various individuals that will come to you from different sides of the issue.

Mr. **EHLERS.** Thank you. I just—switching gears here, continuing on the track you had, Dr. Albritton, and we talked about what is known and what isn't known—I have been very cautious about using the term global warming at all. I mean, it is clear that carbon dioxide in the atmosphere is increasing, and that is a direct measurement. That is a very high certainty that we can make that statement. It is also a fairly high certainty—not quite as high, but fairly high—that that is going to have a climatic effect, because you are trapping energy in the earth's atmosphere.

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I—it seems to me that the climatic effects—we should receive a lot more discussion on the warming effects—they are going to have much greater impact on the human race, for example. But also because of the high heat of vaporization water—of water, and uniquely high heat of vaporization of water that this becomes such a major interactor when you are increasing the energy of the system. And I think that is something very important for the public to understand. Global warming is not the real problem. It may be a problem, but it is not the real problem.

The real problem is what is all the energy going to do to the climate? And what makes this so extremely difficult is that there are going to be good climatic effects and bad climatic effects. And you are then going to have a situation where some people are going to think that greenhouse gases are wonderful because it improved—for example, the people in my area, in the upper Midwest, think El Niño is wonderful. We had beautiful summers, great crops, etcetera, as a result of El Niño. California didn't think it was so great. And that is a microcosm of what is going to happen.

My question to you is, is can you, with any certainty, predict these climatic effects and, if not, when do you expect to be able to calculate those? Are you going to have the earth observation system, or especially ocean observation system, in place first before you will have enough data to really do it accurately? How much better do your computers have to do before you can get into that kind of detail? And I am just looking at timelines of how this is going to happen. Dr. Albritton.

Dr. **ALBRITTON.** Thank you. Two points. Your first one is on your comments and I agree 100 percent, that global warming is not a highly informative term. I don't use that. It wasn't in my notes. And I would much prefer to say change or variability or climate change because that is, in fact, the net effect that people are concerned about that result from the adding the heat to the atmosphere that you have cited.

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I think that your second point, in terms of bringing climate change home, the concept of variability and extremes is the place to focus the information and the information exchange over coming years. The—and that dissolves into two scientific challenges. One is having the observing system in place to see if, indeed, extremes or our regional climate is changing, and then, secondly, having the brain power and the computing power to actually predict on those scales. If I had to give a scorecard at the moment for both of those, the observing and the predicting, is that we—there is a passing grade in that we have a few trends of extremes to find, but not very many. I would give it a C– on that scale.

To be able to predict at the regional level, a particular variable, such as water-related variables, like precipitation, which are more challenging than temperature, we probably have a similar score. And I think the two things that are needed in that area is more in situ observations, particularly in the oceans, and, secondly, better computing power to use the brain power that will be developed from their research.

Mr. **EHLERS.** And is the Argo system going to provide a sufficient—

Dr. **ALBRITTON.** It will be an enormous help for that. It will be an enormous—

Mr. **EHLERS.** Is it sufficient for what we need?

Dr. **ALBRITTON.** It is certainly being planned and very likely to meet the goal stated. And I believe, if we revisit it some years from now, we may find the southern ocean needing perhaps more focus. It is a major part of the planet. It is water world. We are the land world. That is the water world. The heat capacity and circulation of that very large liquid body may well figure in tomorrow's predictions.

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Mr. **EHLERS.** Thank you, Mr. Chairman.

Chairman **BOEHLERT.** The gentleman's time has expired. Mr. Udall.

Mr. **UDALL.** Thank you, Mr. Chairman. And I want to welcome the Panel and particularly note that Dr. Albritton is a constituent and heads the Aeronomy Laboratory at the NOAA site in Boulder. I would also note, for the Committee's interest, that Secretary Evans was in Boulder last Friday and spoke with great interest and respect in Dr. Albritton's work. And I took that as an important sign on the part of the Commerce Department and the Secretary that he was going to do all he could to learn about this issue and continue to support the research.

And, Mr. Chairman, you have, I think, set the right tone here today, which is to ask those of us on the dais here, who tend to have opinions, immediate opinions, about these kind of issues, to keep an open mind. But if I could editorialize, I think that we all ought to be agreeing that research, regardless of where we may end, is something we ought to support. And this—the additional editorial comment I would make is that I think that there are some no-regrets policies we could put in place that would save energy, reduce emissions, and, in the long run, prepare us to respond to climate change if, in fact, it is something that we agree is going to occur once the science has been completed.

In—with that said, Dr. Albritton, I would like to ask you about the IPCC assessment process. You have characterized it as a consensus view. Can you talk a little bit about how you arrive at that consensus? I think a lot of us would be very interested in that.

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Dr. **ALBRITTON.** Thank you. Yes. I would be very pleased to because I believe the IPCC scientific assessment process, as Dr. Kennel pointed out, is an important mechanism whereby the science gets distilled and majority and consensus viewpoints are formed by the experts themselves. And this is put in terms that would be useful to help guide both domestic and international policy. So a few properties of this process.

The most recent stocktaking exercise by the worldwide science community, the so-called third assessment report, has been 3 years in the preparation. It has involved well—hundreds of researchers worldwide. And these, by the way, are aimed to take in as many diverse views about the science as possible, so that it is a large, broad-based opinion-forming group.

The information is based upon the published literature. And that is, it is an assessment of what is out there and not new research, per se. So it has already undergone the individual review of journal articles, scientific debate. And this group now tries to take stock and say, what do we know and what we don't know. It is peer-reviewed twice. A draft is submitted to worldwide experts for an initial review of that. Those reviews are considered taken into the new drafts. A team of editors oversees this to see that the reviews are handled and thought and given that full discourse. Then they are reviewed a second time by experts nominated by individual governments. The United States had its list. The UK had its list, etcetera. So these—this is the second review process.

The final step in that is the taking of the conclusions to the governments. This was done in Shanghai in January where the major points that I summarized for you were presented to governments, questions were asked, terminology was clarified. The message was re-asked and to be more in usable terms and that was a very productive process.

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Three points I would like to see anyone take away regarding the assessment process. Number one, it is the expert community that is preparing the statement, and that contrasts to the single paper, the single viewpoint, the single study that one hears about through newspaper releases, through other accounts. And so it is an averaging and collective taking of opinion.

Second point, it is internationally based. And that is, it is the world community statement, not that of any government group, not that of any sectorial group, or not that of any individual. It is the world community.

And, third, while the information is posed in policy-relevant format, that is, here is our forecast of what would happen if no changes were made; here is our forecast if one made "X" change. It contains no policy prescription. There is no policy recommendation out of this set. Much analogous to when we visit our physician. He examines the system, he makes a—he or she makes a diagnosis, he tells us what our options are, and we leave and take in family considerations, economics, time frame, job, and make those decisions. And so the IPCC report is an attempt to lay out an updated diagnosis of the climate system and our relation to it to clarify options for the future and leave then that as input to a broader set of discussions, much like this hearing. Thank you.

Mr. **UDALL.** It sounds like a very exhaustive process. And to your credit, you don't allow filibusters, like our friends across the capital do. Thank you, Mr. Chairman.

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Chairman **BOEHLERT.** Thank you very much. The Chair recognizes the distinguished Chair of the Subcommittee on Space and Aeronautics, Mr. Rohrabacher.

Mr. **ROHRABACHER.** Thank you very much, Mr. Chairman. First, let me note one of my colleagues has suggested when she visited Antarctica that the scientists kept their mouth shut. Perhaps that is because—not because they agreed with one position or the other, but had observed the 8-year phenomena that scientists supporting global warming get research contracts and, those who oppose global warming theory, generally get fired, which seems to have been the policy of our government for the last 8 years, starting with the firing of Will Harper, who was the head scientist at the Department of Energy, who Vice President Gore made it a point to fire immediately upon entering office because he was an agnostic on the global warming theory.

Gentlemen, I have some specific questions and I only have 5 minutes, so I would like to get answers from you, if I can. What percentage of the CO gases that are going into the atmosphere are put in the atmosphere by natural sources? Just one, two, three, please.

Dr. **ALBRITTON.** A very large fraction of that that resides in the atmosphere is placed there by the burning of—

Mr. **ROHRABACHER.** What would you suggest? What is your guess?

Dr. **ALBRITTON.** Eighty to 90 percent of the—

Mr. **ROHRABACHER.** Eighty to 90 percent. Yes, sir.

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Dr. **MOORE.** The same. But I think what you have to distinguish—

Mr. **ROHRABACHER.** Eighty to 90 percent.

Dr. **MOORE.** —is the change. There are large fluxes to and from the atmosphere from terrestrial systems—

Mr. **ROHRABACHER.** Correct. From volcanoes, etcetera. And I am going to have—follow-up with a question. Eighty to 90 percent. Do you agree with that assessment?

Dr. **KENNEL.** Yeah. I would agree with their assessments, but I wanted to make another point. As you look through the climate—you know, the—

Mr. **ROHRABACHER.** I—listen, I have only got 5 minutes. I need the answer to the question.

Dr. **KENNEL.** A natural balance has been reached in—

Mr. **ROHRABACHER.** I am not—I am asking you to answer the question.

Dr. **KENNEL.** Eighty to 90 percent.

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Mr. **ROHRABACHER.** Eighty to 90 percent. Okay. Now, that, by the way, is an underestimate by other estimates I have heard. I have heard up to 25 percent—excuse me—up to 95 percent, but there is a margin of error there that we can talk about. I noticed that in your chart, Dr. Albritton, that you have here that these are examples from the northern hemisphere. Do the examples from the southern hemisphere have the same result?

Dr. **ALBRITTON.** They do have a similar shape. They are sparser in number because of the lack of observing systems in the southern hemisphere.

Mr. **ROHRABACHER.** Okay. So you are saying that the southern hemisphere—that the tree rings and the things that you have shown and studied in the southern hemisphere, shows the same as the northern hemisphere.

Dr. **ALBRITTON.** It isn't identical because of the difference between land masses and water—

Mr. **ROHRABACHER.** Right.

Dr. **ALBRITTON.** —but the idea of a variation that is on the order of maybe a plus or minus & of degree Celsius—

Mr. **ROHRABACHER.** Right.

Dr. **ALBRITTON.** —looks typical in the southern hemisphere.

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Mr. **ROHRABACHER.** Okay.

Dr. **ALBRITTON.** But the uncertainty bars, which is the gray area—

Mr. **ROHRABACHER.** Okay. Now, I have heard different than that. Let me just say, for the record, that there are some scientists that have suggested that there is a difference in the northern and southern hemisphere in terms of this—these observations. The—and I have noticed even in your own observations here that in 1175 you have almost the same amount of, I guess it is, the global temperature as you have at a year ago. Is there some reason for that? I mean, is this a global warming trend when it is a—your tree rings seem to indicate in 1175 it is the same temperature?

Dr. **ALBRITTON.** Yeah. The message I take away from the blue curves in those figures is that over the 850 years of this millennium at the beginning, temperature varied on the order of a & of a degree Celsius.

Mr. **ROHRABACHER.** Uh-huh.

Dr. **ALBRITTON.** The first 400 years were relatively warm compared to the second 400 years, but the last 150 years have been warmer than all of the preceding 850—

Mr. **ROHRABACHER.** But there were spikes here, you know, and that brings me to one thing. There are natural—of course, we just talked about 80 to 90 percent of all of this is natural. For example, volcanoes certainly—it would cause a spike. Would they not?

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Dr. **ALBRITTON.** Volcanoes certainly do alter temperature—

Mr. **ROHRABACHER.** Okay. But I had one—

Dr. **ALBRITTON.** —but they cause a cooling—

Mr. **ROHRABACHER.** Right.

Dr. **ALBRITTON.** —and it only lasts for a year or two because the particles—

Mr. **ROHRABACHER.** Right. But they also—it also adds a lot of CO in the environment. Doesn't it?

Dr. **ALBRITTON.** The amount of CO from volcanoes is very small compared to the—

Mr. **ROHRABACHER.** All right. Okay.

Dr. **ALBRITTON.** —burning of fossil fuels.

Mr. **ROHRABACHER.** That is good. I just learned something. What about tree rot?

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Dr. **ALBRITTON.** The input of CO to the atmosphere—

Mr. **ROHRABACHER.** From tree rot.

Dr. **ALBRITTON.** Yes. Comes from either burning biomass or the decay of biomass.

Mr. **ROHRABACHER.** Right. So—

Dr. **ALBRITTON.** It is the way it is—

Mr. **ROHRABACHER.** —rotting trees in the forest, in our—what—the rain forests throughout the world, what percentage—how would you relate that to, for example, automobiles?

Dr. **ALBRITTON.** I don't know that comparison quantitatively, but I could say that the uptake by the biosphere and then the release when it dies is observed in the annual record of CO.

Mr. **ROHRABACHER.** Right.

Dr. **ALBRITTON.** The steady of change of the amount of trees growing in the world also has been observed to—

Mr. **ROHRABACHER.** Well, sure. But trees—new trees growing, obviously, help in this problem.

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Dr. **ALBRITTON.** They do.

Mr. **ROHRABACHER.** But old trees rotting in the—

Dr. **ALBRITTON.** They do.

Mr. **ROHRABACHER.** So according to what you—some people in your position are—some people who are global warming advocates—let us put it that way—would be—the best thing would be to clear away all the rain forests and then plant new trees rather than having all those rotten trees out there. Isn't that right?

Dr. **ALBRITTON.** I can't comment that—

Mr. **ROHRABACHER.** Well, that is what seems consistent with me. And then one last thing—one last question, if you will indulge me, Mr. Chairman. We have here some observed changes consistent with warming theory. It says glaciers are retreating, the amount of snow is decreasing, and sea level is going up. Now, and this—have we ever had that in the history of this planet before? I mean, I seem to remember when I was taking my very first class in geology, that they talked about the retreating glaciers and the expanding glaciers that happened over millions of years, even before we got on this planet. Aren't all of those things—weren't those observable even before mankind lit the first fire?

Dr. **ALBRITTON.** Yes.

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Mr. **ROHRABACHER.** All right.

Dr. **ALBRITTON.** All of these changes are natural changes that have been observed to be faster or larger in the last 50 to 100 years—

Mr. **ROHRABACHER.** Okay. Well, I—

Dr. **ALBRITTON.** —than the preceding 1,000 years.

Mr. **ROHRABACHER.** Well, I thank you for saying they were all observable before research—

Chairman **BOEHLERT.** The Chair will indulge the gentleman and extend the time so the witnesses would have an opportunity to answer the question.

Mr. **ROHRABACHER.** I know. But I have got a few questions and one question could be answering the whole thing. I appreciate—

Chairman **BOEHLERT.** No. I understand.

Mr. **ROHRABACHER.** I appreciate your answers. And let me just say your answers have convinced me more research is necessary, which was the position of the Chair. Thank you very much.

Chairman **BOEHLERT.** The gentleman is on record supporting more research. The Chair recognizes Mr. Etheridge.

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Mr. **ETHERIDGE.** Mr. Chairman, thank you for yielding. Let me also thank you for having this hearing on what I consider a very important issue and trust that we can have some bipartisan work together to deal with this very difficult issue. I think it affects us all. But let me bring you to an issue, back to the original issue, you talked about—I think that is how people understand it, how it impacts them and how it hits home. I have the privilege of representing North Carolina and we have seen the deadly forces of hurricanes and tropical storms in recent years. And Hurricane Floyd hit a little over almost 2 years ago now. It was the most costly natural event in the history of our state and one of the largest in this country. We lost 50 lives and, in the process, people in North Carolina have a much better appreciation of El Niño and La Niña phenomena. They don't understand what it is, but when you start talking about weather, they pay attention. And you mention The Weather Channel, and it is probably more commonly watched now, for those who have cable, than ever before in history.

I don't remember who it was who mentioned the educational aspect of it. But I would say that we—I was a state superintendent of schools, incidentally, for 8 years, and we do hurricane drills, we do tornado drills. I think we need to expand that and do a much better job of helping children understand the need. Because what we are dealing with here is the effect and not the cause, and we need to get beyond that.

There seems to be a considerable consensus that there is an issue we need to deal with, and let me get to my question very quickly. What does science tell us about the effects of climate change on tropical storms, their strength and intensity, and where they may have landfall? And I know we are working on that. But, you know, so long we think about hurricanes and—hitting the coastal counties. Well, Hurricane Floyd was 150 miles inland and we have had others who do that. So it is a broader issue now and we need to pay attention to it and I would appreciate having each one of you comment on that, if you would, please.

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Dr. **ALBRITTON.** Yes. A very good point. It is in that class of extreme climate variations which, indeed, have been occurring throughout our history and past records. But we question naturally whether this is to be different in the future or has it already changed. And to go straight to the point, science cannot yet state, with certainty, what will happen to hurricanes and their strength and their infrequency in a warmer world. One may hear from other source's comments, but the scientific community says that this is too difficult a problem to make a statement on at present, and, therefore, comments about increased cost of hurricane disasters is not part of any trend that scientists can point to at the present.

Mr. **ETHERIDGE.** Dr. Moore.

Dr. **MOORE.** Let me just elaborate on that. And using the language that I requested my colleagues and myself use, we think we know that the hydrologic cycle will be intensified. That is, there will be more evaporation, more precipitation. What we don't know is will there be a change in severe storms associated with the intensification of the hydrologic cycle.

Dr. **KENNEL.** The—there is evidence, which is not conclusive, that wave action from storms in the Pacific and Atlantic, have increased over the last few tens of years. So there is some evidence, but I don't think there is a conclusive story.

The most recent snowstorm that occurred around here, sort of a case in point—do you know one of the triumphs was that we knew it was coming 5 to 7 days in advance. The problem was, we didn't predict exactly where it was going to come and when it was going to come. And part of the problem had been that there was a weather system out there in the Pacific that went underobserved until it hit landfall in—on the west coast, and, at that point, it started getting ingested into the models. But until that time, you couldn't—you know, the prediction that people had, based on the information they had, was not accurate enough.

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And the final comment I would make is, is it is my understanding that the Weather Service was extremely careful in predicting—showing its uncertainty about this storm, but, nonetheless, people got attracted to the extreme characterization of it.

Mr. **ETHERIDGE.** Thank you. I am going to try to get one more in before my time runs out because—

Chairman **BOEHLERT.** It had better be a quickie, because you have got 15 seconds.

Mr. **ETHERIDGE.** Well, I will just make a statement in that regard. Because each one has talked about research. It is important to have it. Sometimes we forget the fact of what it costs us not to do it. And in North Carolina, we—the Federal Government invested billions. The state has invested hundreds of millions. That is true all across America. If we look at the cost after, we would probably be a little more prudent and put it into dollars up front for prevention. Thank you, Mr. Chairman.

Chairman **BOEHLERT.** Thank you very much. And I appreciate the Committee's indulgence of the Chair, but we are trying to give everyone an opportunity to get their questions. Mr. Calvert.

Mr. **CALVERT.** Thank you, Mr. Chairman, for calling this hearing and to update what we know about the state of global climate. I would like to say, first off, that I still remain skeptical that climate change is being driven by manmade pollutants—that what is occurring isn't simply natural variability. I will become convinced when someone answers the following persistent questions about climate change science and can persuade me that our understanding is being driven by good consensus science, not just consensus politics.

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First, I am concerned about the quality of the climate models. While they are improving, they do not even begin to capture the complexity of our atmosphere. Last time I was briefed on this subject—and I know I have been briefed on this subject by Dr. Albritton several times—last time I was briefed on this subject, I was informed that there is no way to adequately assess the effect of clouds in the models. I hope we will continue to improve our models and that we will be gaining—gain an accurate idea of what is actually happening, not a bunch of guesstimates based on these incomplete models and data.

That leads me to my second point—the data. We have several sets of data, land-based measurements, balloon measurements, and satellite measurements. The satellite data gives us the most complete coverage of the planet's temperatures yet, while the satellite data shows minuscule warming over the last 20 years or so. The surface temperature record shows rapid warming in the late 1990's. The balloon data tend to agree with the satellites. Surface-temperature data is where the warming is showing up. There have also been some questions about the calibration and location of some of the older land-based weather-data collection stations. Are they giving us data that is accurate as newer systems, and is adequate adjustment being made for the urban-heat island effect?

Also, most of earth's surface is water, and, yet, I see very few data entries from ocean locations. How many climate data points do we have in the ocean to monitor the surface temperature? These issues must be thoroughly addressed.

Third, I haven't seen data to indicate to me that CO is that great a threat, and so I would have to differ with our Chairman and be grateful to the Administration for their statement yesterday. At 360 PPM, I am told, we are at the low end of the historic CO concentrations for Planet Earth. We are up from the incredibly low levels we saw over the past several hundred years. Also, there is a curious observation made by some scientists that temperature increases often precede increases in atmospheric CO. This maybe simply mean that the planet warms more sequestered carbon is released.

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Science also carried a study that suggested that United States might be a net carbon sink, which I think is interesting, meaning that we emit less than our land mass takes up. All of these questions are of a serious concern to me and I would like to hear them addressed in this and future hearings before we set a policy that may have unintended consequences. And with that, gentlemen, convince me.

Dr. **MOORE.** Let me address two of your points, the first and the third. The first, on the role of clouds, in my testimony, I tried to highlight that. That is one of the great challenges. Clouds are on a scale of tens of miles, but cloud systems are on a planetary scale. How to handle that in the computing calculations is a real serious challenge.

However, in the last 5 years, we have made progress. It is not an area where we can point to no progress, but it is still inadequate progress. So that is why I felt that it was important to highlight the role of clouds and the necessary computing resources to, essentially, have the types of models that could address that problem.

Secondly, on your third point, on carbon—two points. One, the CO concentration levels of 360 parts per million are higher than anything we have seen in the last 400,000 years. So if we look back through the last four glacial periods and interglacial periods, we have never seen anything like the concentrations we have today.

Secondly, the study that you spoke about that perhaps the United States or North America is a net carbon sink, is in the published literature and was taken into consideration in the IPCC. What we realize is that while we can talk about the average increase of CO at the planetary scale, we don't have sufficient observations of atmospheric CO to allow us to attribute accurately the sources and the sinks, other than the direct measurement of fossil fuel, which is there for economic reasons we know.

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So that study still stands. There are other studies that say, no, it goes into Eurasia. We don't know. That is an area where additional observations would actually allow us to close that question.

Mr. **CALVERT.** Well, and that is where I will leave off and agree with the Chairman that we do need additional research before we set policy that may have, as I mentioned in my testimony, unintended consequence. And so I look forward to working with the Chairman and the Ranking Member to add to the considerable research that we already have. Thank you.

Chairman **BOEHLERT.** Thank you so much. The Chair recognizes Mr. Larson.

Mr. **LARSON.** Thank you, Mr. Chairman. And let me say at the outset that I concur with additional research and support the position of the Chair and thank the panelists for being here. But let me cut to the chase and hopefully piggyback on something that Ms. Woolsey said earlier. My concern is that with respect to global warming, that, as important as research is, and as we continue this unending debate and clash between academics and scientists over whether the earth is warming or whether it is not, we are faced by many accounts with a severe problem. What kind of strategic plan—assuming tomorrow the scientific community agrees that this is a serious problem with greenhouse warming, what kind of strategic plan would you put in process and how would that relate to the amount of money spent in research as opposed to the amount of money that could be directed at solving the problem?

Dr. **MOORE.** Let me just—two points. I think that there are, without question, things that could be done now. I think we all recognize the so-called no-regrets strategy and various other actions. Frankly, while those are important, they will not go to the heart of the issue. And, therefore, I think we are faced with a very strong political challenge in the future where significant reductions in carbon dioxide would be required. And for such significant reductions, I think that the scientific case will have to be even tighter than it is now. So you have a very delicate balancing match.

Mr. **LARSON.** Along those lines, with respect to a lot of the research developed in fuel cells, is there a downside to water vapor as an emission, as opposed to—you know, when contrasted with regard to COs in the atmosphere?

Dr. **KENNEL.** Not that we know of.

Mr. **LARSON.** Thank you.

Dr. **KENNEL.** I would like to add a remark. Our view on the Global Change Committee was that if you begin now to put in place the integrated end-to-end system that goes from observations to helping people make decisions about their lives, that at the same time that you are doing that, you will begin to build a basis in detailed understanding that will be conveyed to the public and we will start building a platform of understanding of the consequences of climate change or not in the public as they see it working out in their lives, if we can articulate—if we can help it—help them articulate the consequences for themselves.

And so part of the educational effort is simply to start doing the research and conveying the meaning of it to people at—where they live. And if you can do that, then I believe there will be stronger public understanding in the future. People will vote. They will vote their interests, as is natural. And there will be a scientific backing to the way they will go about that process.

Mr. **LARSON.** Was the President's decision yesterday harmful?

Dr. **KENNEL.** Well, what we can say is that if you put carbon dioxide into the atmosphere now, that amount that you put in will last for several hundred years. And if carbon dioxide is a problem, then you have bought a problem later downstream.

Mr. **LARSON.** Thank you for your honesty.

Chairman **BOEHLERT.** The Chair is pleased to recognize another distinguished scientist. This is the Science Committee, after all, and how refreshing it is to have people like Dr. Roscoe Bartlett chairing an important subcommittee and contributing to the work of this Committee. Dr. Bartlett.

Mr. **BARTLETT.** Thank you very much. You know, if I lived in Siberia, you might have a little trouble convincing me that a little global warming would be bad, particularly when I reflected on the fact that, as evidenced by the recent find of a whole woolly mammoth, that my country at one time was very much warmer—as a matter of fact, was subtropical. If we have climate change and global warming, it will be different. I think we need to also determine whether or not globally it would be worse. Different is not necessarily worse.

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But let me ask a technical question about CO. Three-fourths of our planet is covered with water. Water—CO is very soluble in water. In addition to that, there is a lot of phytoplankton in water. This is the beginning of the great web of life in our oceans and phytoplankton needs CO. Also, we have land plants which just barely can make it with the .04 percent CO. They are kind of half-starved. They would do better if they had a bit more CO. Help me with the argument that a little CO wouldn't be a bad thing for our oceans because we would have more life there, and for our land, because plants would grow faster.

Dr. **MOORE.** With respect to the CO in the oceans, it is a fortunate thing that CO is soluble in sea water and that there are phytoplankton, because that is where most of the CO that we emit to the atmosphere ends up. And it because of the oceans that we essentially say only about half stays in the atmosphere.

Secondly, with respect to the fertilization of forests by CO, there are studies that indicate that that is true. The question that we are posed with in the future, though, is how long is that true? When is enough CO enough? There is some point at which the fertilization effect might not appear. We think of terrestrial systems mainly being limited by nitrogen or phosphorus. That is why farmers put nitrogen and phosphorus—they don't put CO—on their crops.

Mr. **BARTLETT.** And we can't put it in the air or we wouldn't—

Dr. **MOORE.** Well, we are doing a pretty good job of it.

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Mr. **BARTLETT.** But the farmer can't put it in the—

Dr. **MOORE.** That is true.

Mr. **BARTLETT.** —air over his farm.

Dr. **MOORE.** That is true. And but your point is well taken, there is a fertilization effect, but how robust is it? How might it change in the future? If you warmed the planet, you will probably both increase the growing season and increase the rate of oxidation, the rate at which material breaks down. Which one wins?

Dr. **KENNEL.** Yeah. I would like to—the Chairman asked for gaps in our knowledge. I would like to outline one of the most basic subjects about ocean carbon. Every thimbleful of ocean water contains a phytoplankton or so and a million species of microbes, most of which have not been identified. They are responsible for 70 percent of the cycling of carbon. Swimming in this symbiotic mixture of phytoplankton and microbes are viruses of unknown function, and it is that assemblage that is responsible for the overall ocean's role in retirement of carbon.

We do not know the genomic sequence of this collection of microbes. Until we know how these little chemical factories work and know the instructions on which they are working, we won't know whether—how that system will respond collectively to—

Mr. **BARTLETT.** Let me ask another question relative to CO and warming. Certainly it is a greenhouse gas. But almost any process which—at least most of the processes which produce CO, also produce a lot of particulate matter. Particulate matter in the air can cool our earth. As a matter of fact, we do have a global cooling, after a large volcano goes off, from the trash that is thrown up there. How are we sure that the earth is not going to be cooled by the burning of things which produce CO rather than warm? Certainly you have the greenhouse gas effect, but you also have the effect of particulates, and that is kind of a cloud effect. And how do we know which of those is going to predominate?

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Dr. **KENNEL.** This is one of the areas where improved observing systems would help, because it all depends on the particulates that are emitted and where they emitted from, and who is doing it. For example, it is true that volcanoes are cooling and the sulfate aerosols from North America are cooling and they have been used in the models. But a recent experiment that was done over the Indian Ocean found that 11 percent of those particles were black soot and they were warming. They were warming the lower atmosphere and cooling the top of the ocean.

And so we have—we now understand that not all aerosols are created alike or do the same thing and that they—we also know from just common observation, over China, over India, over northeast America, they are spread now from cities to regional scale and can affect the climate. We don't—and the direction will depend on what they are made of.

Dr. **ALBRITTON.** Just to add a footnote to that, yes, you are exactly right to say the burning of fossil fuels does release CO and it does release sulfur that leads to particles. And exactly the CO is a warming effect and most of the particles are a cooling effect. But those particles also have been involved in other environmental issues, like acid deposition. And many countries, particularly the United States and Western Europe, have begun to scrub and remove those particles to where they—there is expected to be a decline in the cooling term associated with fossil fuel burning. So and not only do we have to understand the science behind the two effects, but we also have to understand what the trends are in their relative contributions.

Mr. **BARTLETT.** Mr. Chairman, my—the—my emphasis was not to indicate that I think that burning fossil fuels is a good idea in producing CO. I was just trying to indicate that we need more scientific information and understanding of these things. I think that we will all benefit, as a matter of fact, if we are burning less fossil fuels and producing less CO and less of the particulate matter that comes from burning fossil fuels.

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Chairman **BOEHLERT.** I can subscribe to that theory 100 percent. Thank you. The Chair is pleased to recognize Mr. Wu.

Mr. Wu. Thank you, Mr. Chairman. I have only one short simple question. I am not sure if the answer can be quite as short or simple. But for the whole Panel, how far away are we from a technologically and economically feasible hydrogen technology for many of our fuel needs?

Dr. **MOORE.** I don't know.

Mr. Wu. Well, it was amenable to a short simple answer. Thank you, Mr. Chairman. I yield back the balance of my time.

Chairman **BOEHLERT.** Thank you very much, Mr. Wu. The gentleman—the Chair is pleased to recognize the distinguished Vice Chairman, Mr. Gutknecht.

Mr. **GUTKNECHT.** Thank you, Mr. Chairman. I left Minnesota yesterday, and in my back yard we have over three feet of snow. In Rochester, Minnesota we have not seen 40 degrees since November 6. So on behalf of my constituents, if global warming be a scientific fact, I would say let us have more of it.

I really am happy today, at least, with the tone of the discussion, because I think to a certain degree, this whole issue has been politicized over the last number of years and I think we all need to take an honest and sober look at it and really look at the evidence. The other thing that has disturbed me, and this is more of a statement than a question, is that there has been sort of an attitude that we are sort of throwing up our hands and saying, well, oh, woe, is me, the planet is going to warm. That is not the nature of Americans, at least, you know.

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To paraphrase what Winston Churchill said many years ago, we did not cross the oceans, traverse the mountains, deal with the droughts and pestilence because we are made of sugar candy. I think we will find solutions. And maybe it is in hydrogen; maybe it is in other forms of energy. But I really don't think we should just throw up our hands and say, everybody has got to give up their automobiles. I don't think that is going to be acceptable to Americans.

You mentioned earlier in your discussions about fertilizing the oceans and sort of set that aside as not a very acceptable solution. I am curious as to why.

Dr. **MOORE.** Actually, we were talking about the CO fertilization of terrestrial vegetation, just simply by their being more CO in the atmosphere. There is, however, and I think is the point that you are driving at, an issue that some people are proposing, that is, that parts of the ocean are deficient in iron—

Mr. **GUTKNECHT.** Correct.

Dr. **MOORE.** —and that we adopt a Geritol strategy for the oceans. I think the challenge there is to how much real sequestration would you get? Are you simply buying a little time or are you actually really storing carbon over the long pull? And, secondly, how much carbon does it actually take to implement such a strategy? What is the net effect? And, finally, what are some of the other environmental consequences? I think that is a very chancy business. I would be—I think we need to know more about the ocean's storage of carbon. We might use experiments like the fertilization experiments to try to understand that. But I think to adopt that as policy—I think there are other ways that we can cross the ocean.

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Dr. **KENNEL.** A lot the carbon compounds that find their way to the bottom of the ocean, when we dredge them up, they immediately go unstable. And so what is not known about the sequestration of newly deposited carbon would be, would it remain stable on the ocean bottom in solid form for a comfortable length of time? It is an unknown question—an answer—unknown answer to that question.

Mr. **GUTKNECHT.** Well, this may seem like a somewhat facetious question, but I would like to get your response to it. I am told that an acre of growing corn in my district in the upper Midwest, consumes five times more carbon dioxide than an acre of old growth forest. Does that square with your research?

Dr. **MOORE.** The problem with that is that the acre of growing corn at the end of the growing season is harvested. That material doesn't stay around. Some of it is shipped off to places where it is oxidized, i.e., eaten. Or the other material stays around and it oxidizes. In Minnesota and elsewhere, we don't have large stacks of ungrown corn lying around.

Mr. **GUTKNECHT.** Oh, yes, we do.

Dr. **MOORE.** Field agricultural surpluses. It—your point, though, is well-taken though that there are strategies that we could implement that could increase the storage of carbon in agricultural soils. And we know that because we have lost a lot of carbon in agricultural soils and we could, perhaps, reverse that. So we might think about policies that would essentially try to do that. That certainly is a win-win strategy anyway.

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Mr. **GUTKNECHT.** Well, and I will say this, Mr. Chairman, on behalf of the people who are here, I mean, there are people at some of our Ag schools who are looking at exactly that. And there are—I mean, I guess, my real concern is that we not, as a society and a scientist, begin to throw up our hands and say, well, there is just nothing we can do. I mean, we will find ways to solve these problems. That is the history of this country.

And I would like to put a more optimistic spin on this thing. I tend to agree, though, that all global warming and all elevation of CO in the atmosphere is not necessarily a completely bad thing. I mean, at some point it—I do understand that it will have severe and negative consequences. But from a historical perspective—and one last—and see my red light is on. But I mean, it is true that from a historical perspective, if you look over the last million years that we can measure it all, that we are at a low level relative to CO in the atmosphere today than we have been relative to, say, the time of the dinosaurs. Is that correct?(see footnote 3)

Dr. **MOORE.** No. That is not correct. You could look over the last 5 million years and we have never seen levels this high. We have a very good record for the last 400,000 years and we are well above—

Mr. **GUTKNECHT.** Now, I want to make—let me make sure I am clear in this. You are saying that the level of CO in the atmosphere is higher today than at the time of the dinosaurs, because that is not what I have been told.

Dr. **MOORE.** Five million years ago—

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Mr. **GUTKNECHT.** I am sorry. I couldn't hear you, please. We will wait until the bells stop.

Dr. **MOORE.** Okay.

Chairman **BOEHLERT.** We have a series of votes. So the gentleman's time is expired. We will let you finish this, Dr. Moore, your response, and then we will go to Mr. Hall and then we—who is next on the list—and then Mr. Grucci and then we are going to have to respond to the votes, and it appears there is going to be a series of votes. So it is unfair to expect everyone to be captive here because you would have to wait around a half-hour or so. So we will conclude the hearing and we will—pardon me—and we will have an opportunity for written submissions. Mr. Smith is before Mr. Grucci. Mr. Hall. Yeah. Dr. Moore, did you have a quick response to Mr. Gutknecht's question?

Dr. **MOORE.** Congressman, certainly the—we have very good records over the last 400,000 years. We have—we never saw anything above 300 PPM over the last 400,000 years. And I believe over the last 5 million years, we have never seen levels at the 360, 370 that we are at now.

Chairman **BOEHLERT.** Mr. Hall.

Mr. **HALL.** Thank you, Mr. Chairman. I am sure that you saw the article that the New York Times and the Washington Post commented on. One, "Bush Drops a Call for Emission Cuts. Backing Away From Pledge, Bush Will Not Regulate Carbon Dioxide." You gentleman have all seen that. Have you not? Let me ask you if—there are a number of different estimates regarding the increase in worldwide temperature over the last century, and there is a lot of differences of opinion, as you all well recognize.

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And let me say to start with, and I don't want to lessen or diminish my respect for you, your background, or your knowledge, because I really believe that you believe what you are testifying to. There are those, though, eminent in your field who vehemently disagree with you. Are there not? Is that an accurate statement?

Are you familiar with a person named John Christie? Have you read of his—I think he is a Director in the Earth System Science Center at the University of Alabama at Huntsville. One of the world's most respected climatology experts, so an author from the Tulsa World Herald opines. And he points out that the protocol calls for just a vast expenditure of wealth from the United States, from Europe, and from Japan, to emerging nations, such as China, India, and Indonesia, as well as a lot of the poorer nations of Latin America, Africa, Asia. And that Americans would sacrifice thousands of dollars in lost savings if some of your positions are inaccurate and the positions taken by Richard Lindzen and John Christie are accurate.

And I am going to ask you a question about that. In December 1997, I think you must remember that the United States Senate took a look at the Kyoto numbers and voted 95 to 0 in favor of a resolution deploring the disaster that the treaty would foist on the United States economy. You all are aware of that vote. So, as a result, the Clinton Administration didn't send the treaty to the Senate for ratification because, you know, 95 to 0 is a pretty overwhelming and a resounding defeat for that thrust.

But instead, he initiated a sweeping program to try to implement it by regulation and by Executive Order and logically. And I think logically most of these are being rescinded by the Bush Administration. So the only chance for the UN to superimpose its science requirements, that these men deplore, on the United States, is some way to panic the American public. Those were his words, not mine. I would like your opinion on that. Dr. Albritton.

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Dr. **ALBRITTON.** Yes. I can comment on the temperature record. The numbers that were cited here were the results from several hundred scientists worldwide.

Mr. **HALL.** And where were those taken?

Dr. **ALBRITTON.** They were taken all over the world, surface and vertical temperatures, northern hemisphere and southern hemisphere. So—

Mr. **HALL.** Now, when I asked you when the surface temperature is measured, where and how is it measured?

Dr. **ALBRITTON.** It is measured at the weather stations of many nations. It is also on weather balloons and on satellites. The point that you mentioned about the difference between the satellite record and the surface record was incorporated in this summary that—from which we quoted. And I know Dr. Christie very well. He was also one of the authors that prepared this temperature record. So he was a member of the group that formulated this statement on temperatures.

Mr. **HALL.** Okay. I think my time is expired. If I might, Mr. Chairman, I would like to submit some questions to you in writing.

Chairman **BOEHLERT.** Yes.

Mr. **HALL.** And I thank you and I thank you for your time.

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Chairman **BOEHLERT.** Yes. And all Members of the Committee will be afforded the opportunity to submit questions in writing, and we would very much appreciate thoughtful and timely responses, which is exactly what we would expect from this distinguished Panel. Mr. Smith.

Mr. **SMITH.** Thank you, Mr. Chairman. Just a follow-up on Richard Lindzen. He and some of his colleagues at NASA indicated that satellite measurements of sea surface temperature and cloud cover over the Pacific Ocean indicated that the earth had a natural heat vent. Was this taken into consideration in the models that IPCC developed?

Dr. **ALBRITTON.** A quick comment on that. Dr. Lindzen was a member of the group that wrote the chapter on climate models, their strengths and their weaknesses. So his viewpoints—well, he had the opportunity to put his viewpoints into that. I think the paper you cite was just published in the last few days. Since those papers go through a review process and since Dr. Lindzen was part of the preparation of this climate statement, I am assuming that his viewpoints were taken into account, that his membership—

Mr. **SMITH.** And let me sort of follow up on Mr. Hall's questioning. I was one of the Representatives of the House at COP–6 over in the Hague. And former President Clinton and former Vice President Gore approved an offer that we made, sort of a compromise, that Europe eventually turned down. Give me your opinions on the offer and whether or not maybe Europe was looking for more of a scapegoat or more of a performer in terms of the United States doing more. What—do you have an opinion on the compromise offer that was turned down? Would we have been better ahead if we went ahead with that?

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Dr. **ALBRITTON.** Well, I was not at COP–6. I don't own a policy hat, so I couldn't put the one on. Maybe others had some perspective on that negotiations. I don't.

Dr. **MOORE.** No. And I think that that is outside my level of expertise.

Mr. **SMITH.** Well, it is sort of the level of expertise, because it is policy, but policy overlaps with what the real world is, it seems to me, in terms of how do we move ahead and at least take a closer look at what we are, as humans, doing in our industrialized society.

Dr. **MOORE.** I think it certainly is clear, Congressman, that the human species are going to have to find ways of reducing fossil fuel emissions. It is a real problem and it is a long-term problem.

Mr. **SMITH.** And, Mr. Chairman, if I can submit some other questions, if I could, in writing—

Chairman **BOEHLERT.** By all means, the gentleman—

Mr. **SMITH.** —I would appreciate the opportunity to do that. Thank you, Mr. Chairman.

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Chairman **BOEHLERT.** Let me—we have 5 minutes and 52 seconds before we have to vote and hope for a second round. There is a great deal of interest in this subject, particularly the input from this Panel. But it is unfair to continue this hearing and expect you to wait another half hour. You have busy schedules. Let me conclude by thanking you for serving as resources. Let me observe that in the history of recorded science, there probably are very few times when there is 100 percent certainty on anything. Is it fair to say that there is general scientific consensus that global climate change is for real?

Dr. **MOORE.** Yes.

Dr. **KENNEL.** Yes.

Dr. **ALBRITTON.** Yes.

Chairman **BOEHLERT.** Is it fair to say that the human element, in terms of contributing to the issue is there—it exists?

Dr. **ALBRITTON.** Yes.

Chairman **BOEHLERT.** And would you acknowledge that we have to do more with research to fill the information gaps?

Dr. **ALBRITTON.** Yes.

Dr. **KENNEL.** Yes.

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Chairman **BOEHLERT.** So the questions that will follow to the Panel will be with some specificity. We are talking in the computational science, that type of thing, if you could. And I am not asking you to do our work. I am asking you to guide us. Tell us where we need to focus the resources because it is clear we need to. There are skeptics and there are those of us who are less skeptical. And we need some support—the proper support for the Federal scientific enterprise to remove the skepticism and to confirm theories one way or the other.

But I want to thank you very, very much. You are performing a very valuable service for this Committee, this Congress, and this country. This hearing is adjourned.

[Whereupon, at 12 p.m., the Committee was adjourned.]

APPENDIX 1: Footnotes

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APPENDIX 2: Opening Statements

PREPARED STATEMENT OF CONGRESSMAN SHERWOOD BOEHLERT

It's a pleasure to welcome everyone here for the third of our three opening hearings on the Committee's priorities for the 107th Congress—education, energy and the environment. The subject of today's hearing is the environment, and specifically, global climate change.

I think it's safe to say that this is the most controversial of our three opening topics. But there is one principle concerning global climate change on which just about everyone can agree—and that's that we need a strong and continuing research program to understand more about climate. And it's that research program that is our primary focus this morning.

Our witnesses, in particular Dr. Albritton, will review the current state of the science. But all our witnesses have been asked to highlight the gaps in our knowledge of climate change and what we might do to fill them. This Committee created the U.S. Global Change Research Program, which is due for an evaluation and perhaps some additional legislating. Today's hearing will help us assess whether the federal government's research program needs to be restructured and/or redirected and whether its funding is adequate.

Obviously, the science of climate change has policy implications. I wish the Administration would have waited to hear from experts like the ones we have before us today before embarking on what I believe is a misguided and unjustified reversal of position. But policy is not what we are focusing on at today's hearing. We will have additional hearings at both subcommittee and full committee on the policy implications and on the science itself.

So I urge my colleagues to focus today on the state of the science of climate change, and especially on the future research agenda for understanding climate change. What are the outstanding gaps in our knowledge? How and when might we get answers to those questions? These issues have not been the subject of many recent hearings.

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So, I look forward to an open and vigorous—and rigorous—conversation about those matters, one that I hope does not simply rehearse previous discussions of this issue.

PREPARED STATEMENT OF THE HONORABLE EDDIE BERNICE JOHNSON

Thank you, Mr. Hall, for this opportunity to speak today on global climate change, an issue I take very seriously.

Last November, I attended the UN Framework Convention on Climate Change (COP–6) at the Hague, Netherlands. There were many technical issues discussed there including credits for carbon sinks, how to deal with countries that do not meet emission reduction goals and how developing countries obtain the financial resources necessary to deal with the adverse effects of climate change.

This last point was important to me. While the focus of today's hearing is on the science of climate change, we must remember the human dimension of climate change—those who stand to gain and lose the most from changes in global weather patterns.

We do not need to model the future to understand how devastating current weather is on the less affluent countries and people in the world. Hurricane Mitch which destroyed large parts of Central America and droughts in Africa, which continue to cause starvation are but two examples of the human suffering brought on by severe weather.

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Taking practical steps to reduce people's vulnerability to today's weather would go a long way to solving the problem of tomorrow's climate.

Currently, we have gridlock. Scientists have studied the question of climate change in detail for at least the last ten years. With every new understanding come more questions that need to be answered. The big question is when is the time to move beyond the research into mitigation?

I hope our distinguished panel can share some light today on this matter. The time has come for us to be able to tell the world that we better understand the world's climate and can make change that will make a difference.

Thank you.

PREPARED STATEMENT OF REPRESENTATIVE LYNN WOOLSEY

Mr. Hall, thank you for yielding.

Two weeks ago at this Committee's hearing on energy, our panel [of witnesses] briefly touched on climate change when they spoke about the effects and implications of our nation's reliance on fossil fuels. I was especially encouraged by their remarks on this subject because they were *nonpartisan* witnesses who were basing their comments on scientific understanding.

I commend the Chairman for holding this hearing so we can learn more about the *science* behind climate change. At the heart of climate change science is a well-established theory, "the greenhouse effect," that states carbon dioxide emissions—a heat-trapping gas that is produced by the burning of fossil fuels—significantly contributes to the global warming trend.

That's why I'd like to draw the Committee's and Panel's attention to a recent statement by the Vice Chair of the U.N.'s Intergovernmental Panel on Climate Change. He said that the challenge of cutting carbon emissions should, in part, be viewed as *an opportunity* to develop new technologies to reduce emissions.

I am confident that as a society we can reduce carbon emissions if we develop clean fuel technologies, like green and renewable energy resources, that don't result in harmful carbon dioxide emissions.

I'm hoping our distinguished panel will comment on research needs that will leave the planet as healthy for our grandchildren as it was for our grandparents.

Thank you.

PREPARED STATEMENT OF JERRY F. COSTELLO

Energy plays a critical role in our economy. As a result, I believe it is in the nation's best interest to make improvements in energy efficiency, to diversify our use of energy resources, and to expand energy supplies. The coal industry is of great importance to my district in Southwestern Illinois which, as you may know, is rich in high-sulfur coal. The shifting of production to low-sulfur coal has cost many of my constituents high-paying jobs. I support research and development of cleaner fossil fuel initiatives which includes a program to develop new technologies for cleaner, higher efficiency coal combustion with the hopes of achieving a healthier environment.

I am also looking forward to hearing more about non-fossil energy sources including ethanol, solar power, and wind energy. I welcome our panel of witnesses and look forward to their testimony.

APPENDIX 3: Written Statements, Biographies, Answers to Post-Hearing Questions, and Financial Disclosures

PREPARED STATEMENT OF DANIEL L. ALBRITTON

Good morning my name is Dan Albritton. I am Director of the Aeronomy Laboratory of NOAA Research. Thank you for the invitation to report the findings of the recent report of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was set up jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international statement of scientific opinion on climate change.

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The Laboratory that I direct is located in Boulder, Colorado, and studies the global chemistry and dynamics of the Earth's atmosphere. Scientists in our Laboratory have played major roles in understanding the stratospheric ozone layer, greenhouse gases, and regional air quality.

I have also been involved in providing scientific information to policymakers in government and industry, including both those in the U.S. and internationally, on the ozone layer and the greenhouse effect. Most recently, I served as one of the Coordinating Lead Authors of the state-of-understanding assessment of the IPCC: "Climate Change 2001. The Scientific Basis".

I appreciate the invitation to appear before your Committee and to summarize the current state of scientific understanding of the climate system. My information is based on the set of findings of the recent IPCC report, which has been three years in preparation and which was completed last month. This assessment represents the work of over a hundred scientific authors worldwide. It is based on scientific literature, and was reviewed by hundreds of scientific peers. It is the understanding of these authors that I am pleased to summarize here today.

Before addressing the new findings of the recent IPCC report, let me note two points that have been long-known, very well-understood, and deeply underscored in all past IPCC reports and other such scientific summaries:

The "greenhouse effect" is real, and it is a natural part of our planet. A small percentage (2%) of the atmosphere is, and long has been, composed of greenhouse gases, which are constituents such as water vapor, carbon dioxide, and methane that effectively prevent part of the heat radiated by the Earth's surface from otherwise escaping to space. The global system responds to this trapped heat with a climate that is warmer, on the average, than it would be otherwise without the presence of these gases.

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Why then, if the greenhouse effect is a natural part of the planet, is it referred to as "an issue"? The reason is that it has been very clear for some time that we are changing the greenhouse radiation balance, namely:

Greenhouse gases are increasing in the atmosphere because of human activities, and increasingly trapping more heat. Direct atmospheric measurements made over the past 40-plus years have documented impeccably the steady growth in the atmospheric abundance of carbon dioxide. In addition to these direct real-time measurements, ice cores have revealed the atmospheric carbon dioxide concentrations of the distant past. That is, measurements using the air from bubbles that were trapped within the layers of accumulating snow show that atmospheric carbon dioxide has increased by about 30% over the Industrial Era (since 1750), compared to the relatively constant abundance that it had over the preceding 750 years of the past millennium. The predominant cause of this increase in carbon dioxide is the combustion of fossil fuels and the burning of forests. Moreover, methane abundance has doubled over the Industrial Era. Similarly, other heat-trapping gases are also increasing as a result of human activities.

But, what do these changes in greenhouse gas abundances imply for changes in the climate system? Indeed, what climate changes have been observed, both recently and earlier? How well are the causes of those changes understood? Namely, what are natural changes and what are changes due to greenhouse-gas increases? And, what does this understanding potentially imply about the climate of the future?

These questions relate to the scientific points that you asked me to address today. In doing so, I will summarize three major conclusions from the recent IPCC climate-science report. These conclusions are based, in order, on measurements, analyses, and projections, which are, of course, understandably in an order of decreasing scientific confidence.

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There is a growing set of observations that yield a collective picture of a warming world over the past century. The global surface temperature very likely has increased over the 20th century by 0.7 to 1.4 degrees Fahrenheit. The average temperature increase in the Northern Hemisphere over the 20th century is likely to have been the largest of any century during the past 1,000 years, based on "proxy" data (and their uncertainties) from tree rings, corals, ice cores, and historical records. (See Figure 1, IPCC Working Group I

Summary for Policymakers, 2001) Other observed changes are consistent with this warming. There has been a widespread retreat of mountain glaciers in non-polar regions. Snow cover and ice extent have decreased. The global-average sea level has risen between 4 and 8 inches, which is consistent with a warmer ocean occupying more space because of the thermal expansion of water.

There is new and stronger evidence that most of the warming observed over the last 50 years is attributed to human activities. The 1995 IPCC climate-science assessment report concluded: "The balance of evidence suggests a discernible human influence on global climate." Although many of the sources of uncertainty identified in 1995 still remain to some degree, new evidence and improved understanding support the above updated conclusion. Namely, recent analyses have compared the surface temperatures measured over the last 140 years to those simulated by mathematical models of the climate system, thereby evaluating the degree to which human influences can be detected. Both natural climate-change agents (solar variation and episodic explosive volcanic eruptions) and human-related agents (greenhouse gases and sulfur-containing fine particles) were included. The natural climate-change agents alone do not explain the warming in the second half of the 20th century. The best agreement between observations and model simulations over the last 140 years is found when both human-related and natural climate-change agents are included in the simulations. (Compare Figures (4a) and (4c), IPCC WG I SPM, 2001) In light of such new evidence and taking into account the remaining uncertainties, the IPCC scientists concluded that most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

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Based on scenarios of future human activities, global average temperature and sea level are projected to rise over this century. Clearly, the atmospheric abundances of greenhouse gases over the next 100 years cannot be predicted with high confidence, since, the future emissions of these gases will depend on many diverse factors, e.g., world population, economies, technologies, and human choices, which are not uniquely specifiable. Rather, the IPCC assessment endeavor aimed at establishing a set of scenarios of greenhouse gas abundances, with each based on a picture of what the world plausibly could be over the 21st century. Based on these scenarios and the estimated uncertainties in climate models, the resulting projection for the global average temperature in the year 2100 ranges from 2.5 to 10 degrees Fahrenheit (See Figure 5, IPCC WG I SPM, 2001). Such a projected rate of warming would be much larger than the observed 20th-century changes and would very likely be without precedent during at least the last 10,000 years. The corresponding projected increase in global sea level by the end of this century ranges from 3.5 to 35 inches. Uncertainties in the understanding of some climate processes make it more difficult to project meaningfully the corresponding changes in regional climate. However, it is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season. Further, it is very likely that many features of the weather will become more variable, e.g., higher maximum temperatures over nearly all land areas and more intense precipitation events over many areas.

The last point that I would like to make is not a "new finding". Indeed, it has been underscored with very high confidence in all of the IPCC climate-science assessment reports (1990, 1995, and 2001). I repeat it here because it is a key (perhaps "the" key) aspect of a greenhouse-gas-induced climate change:

A greenhouse-gas warming could be reversed only very slowly. This quasi-irreversibility arises because of the slow rate of removal (centuries) from the atmosphere of many of the greenhouse gases and because of the large resistance of the oceans to thermal changes. For example, several centuries after carbon dioxide emissions occur, about a quarter of the increase in the atmospheric concentrations caused by these emissions is projected to still be in the atmosphere. Additionally, global average temperature increases and rising sea level are projected to continue for hundreds of years after a stabilization of greenhouse gas concentrations (including a stabilization at today's abundances), owing to the long timescales (centuries) on which the deep ocean adjusts to climate change.

Let me close, Mr. Chairman, with an important "sidebar" point. As noted, the IPCC climate-science assessment is the considered viewpoint of hundreds of scientists worldwide. This assessment is based upon the research results of the worldwide community that are published in numerous scientific journals. The resulting report contains policy-relevant scientific information, but makes no policy statements or recommendations. *As such, the three components of the 2001 IPCC Third Assessment Report—climate science, impacts, and mitigation—are commended to you as a key information source (indeed, as a touchstone) that is available to you and others as you continue this important dialogue about climate change and its relation to humankind.*

Thank you for the invitation to appear today. I hope that this summary has been useful. I would be happy to address any questions.

Source of cited information:

Summary for Policy Makers, Climate Change 2001: The Scientific Basis B Contribution of Working Group I to the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. Currently available at *http://www.ipcc.ch* The full report will be available this summer from Cambridge University Press.

Parallel IPCC reports:

Climate Change 2001: Impacts, Adaptation and Vulnerability—Contribution of Working Group II to the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report.

Climate Change 2001: Mitigation—Contribution of Working Group III to the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report.

BIOGRAPHY FOR DANIEL LEE ALBRITTON

Birthplace: Camden, Alabama. 8 June 1936.

Education: Georgia Institute of Technology, B.S. Degree, Electrical Engineering, 1959; Georgia Institute of Technology, M.S. Degree, Physics, 1963; Georgia Institute of Technology, Ph.D. Degree, Physics, 1967.

Position: Director, Aeronomy Laboratory; Office of Oceanic and Atmospheric Research; National Oceanic and Atmospheric Administration; U.S. Department of Commerce

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Aeronomy Laboratory. Dr. Albritton has directed the Aeronomy Laboratory of NOAA Research in Boulder, Colorado, since 1986. The research of the Aeronomy Laboratory is focused on understanding the chemistry and dynamics of the atmosphere. Several key environmental issues are being addressed: stratospheric ozone depletion, acid deposition, tropospheric ozone production, tropical ocean/atmospheric interactions, and the greenhouse effect. The Aeronomy Laboratory is staffed with approximately 100 scientists, engineers, and support personnel.

Personal Research. Dr. Albritton joined the Aeronomy Laboratory in 1967, where he conducted research in the laboratory investigation of atmospheric ion-molecule reactions and theoretical studies of diatomic molecular structure. In later years, his research interest was the field investigation of atmospheric trace-gas photochemistry. He has published approximately one hundred and fifty papers in these research areas, has been invited to contribute numerous review papers, and has lectured nationally and internationally on these subjects.

NOAA National and International Research Planning. He leads the Atmospheric Chemistry Project of NOAA's Climate and Global Change Program. Dr. Albritton has been one of two coordinators of the drafting of the research plan for the U.S. Global Change Research Program. He has been a member of review and steering groups for the National Academy of Sciences, other-Agency and private-sector programs, and international research efforts, such as the International Global Atmospheric Chemistry Program. He is the Science Vice-Chair of the Air Quality Research Subcommittee of the Interagency Committee on Environment and Natural Resources.

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Science Advisor in Ozone Depletion. For over a decade, Dr. Albritton has served as Co-chair of the scientific assessments of stratospheric ozone. In this capacity, he helps provide the scientific basis for the United Nations Montreal Protocol on Substances that Deplete the Ozonc Layer. He has testified frequently before the Congress on this topic.

Science Advisor in Climate Change. He is one of the Coordinating Lead Authors of the state-of-understanding assessments of the lntergovernmental Panel on Climate Change (IPCC) climate-science working group. He has given briefings to the Agencies and Members of Congress on the findings of these assessments.

Recognition and Awards. Dr. Albritton is a Fellow of the American Physical Society and of the American Geophysical Union. He has served on the Editorial Advisory Board of the *Journal of Molecular Spectroscopy* and the *Journal of Atmospheric Chemistry* and as co-editor of the latter journal. Dr. Albritton has received several awards and honors for outstanding performance in NOAA, including two Department of Commerce Gold Medal Awards and the Presidential Rank Distinguished and Meritorious Service Awards. Other awards include the 1993 Scientific Freedom and Responsibility Award from the American Association for the Advancement of Science, and a special award from the American Meteorological Association for scientific assessments of the understanding of stratospheric ozone depletion.

POST-HEARING QUESTIONS

Replies from Dr. Daniel L. Albritton

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Note Regarding Each Answer:

Many of the post-hearing questions relate to current research needs. In answering these questions, the aim of the replies below is to list the few most-important current information gaps that relate in the immediate term to informed decision-making by governments, industry, and the public, being as specific as possible. Namely, the most-needed "next-step" research is identified.

The approach taken in the replies is the following. With each major information gap, this summary also gives the *implied research needs* (the "What?") and *the resulting payoffs* for decision-making (i.e., the "So what?"). In addition, *time scales for improvement in policy-relevant information* are estimated.

Subsequent to the March 14th hearing, President Bush announced a new U.S. Climate Change Research Initiative. He has directed the Secretary of Commerce, working with other agencies, to set priorities for additional investments in climate change research, to review such investments, and to improve coordination amongst federal agencies. That review process is just beginning, and the following answers are subject to the results of that review. I expect, however, that the review will provide more specific answers to your questions when it is completed.

Question: (Asked to all witnesses) In the near- and long-term, what can or should be done to stabilize existing observational capabilities and to identify crucial variables that are inadequately measured at present? What monitoring capabilities will we lose if we do not take action?

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Answer:

A recent report of the U.S. National Academy of Sciences addressed these issues ("Adequacy of Climate Observing Systems," National Research Council, U.S. National Academy of Sciences, 1999). It is a very authoritative study of the "state of health" of the current climate observing system. In my view, there is no better set of broad recommendations related to repair/improvement of the climate observing system than that given on pp. 5–6 of this NRC report.

In terms of the needed augmentations to our observations of climate change, the most relevant specifically to the filling of gaps that currently limit decision-making are, in my view, the following:

Higher-resolution precipitation data. *Research Foci:* Beyond surface temperature, precipitation is perhaps the next—most societally—crucial climate variable. A better network (i.e., calibration, sampling skill, and coverage) will show regional trends and variations, both of which are poorly characterized at present. *Payoffs:* Local and regional managers (e.g., water availability and droughts) will have new "climate-normals" baselines upon which to base decisions. Very importantly, the data will test/improve the capability of climate models to predict this crucial variable.

Monitoring of polar climate-relevant parameters (e.g., ice extent and thickness). *Research Foci:* Some of the largest climate changes are predicted to occur at high latitudes, where data are very sparse: e.g., temperature, freeze-free season length, sea-ice thickness. Further, the surface reflectivity of these regions is a major feedback process in climate models. *Payoffs:* Measurements to track such changes in polar regions would test the predictive skill for this big signal. Arctic changes (e.g., loss of snow and ice cover) are large and likely-irreversible changes, so "getting it right" early on (i.e., observations/predictions) will be extremely important to confidence in predictions of further climate change.

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Improved in-situ observations of surface forcing agents (factors that affect heating, e.g., wind and heat flux) for the ocean. *Research Foci:* The ocean controls the "pace" of climate change. The exchange of energy between the "fast-responding" atmosphere and the sluggish ocean must be better characterized for better long-term predictions. Surface atmospheric data are routinely collected from ships, fixed buoys, and surface drifters. While this network serves the numerical weather prediction goal adequately, the quality and quantity of these data do not meet the needs for better climate change prediction. A concentrated effort is required to improve the meteorological observations from a subset of the observing fleet and to deploy additional fixed platforms. *Payoffs:* These data will (i) help ensure that climate signals can be distinguished from instrument signals, (ii) provide continuous calibration/validation observations for satellite-based measurements of oceanic factors that affect climate; and (iii) help provide the information needed to attribute the cause of climate signals.

Quantitative observations of extreme events. *Research Foci:* Severe storms and hurricanes have momentous impacts, but the characterization of the trends is non-existent at present. Homogeneous data on the characteristics of extreme events, both current and in the past, are required, e.g., frequency of occurrence, tracks, intensity, and rainfall amount. *Payoffs:* A decade or so of solid trends would be one of the most relevant messages to the public about climate change. Further, such data would help develop an extreme-event predictive capability in the next generation of climate models, now only in a fledgling stage.

To address the last part of the Committee's question, regarding what monitoring capabilities we would lose if no action is taken: Researchers would lose the opportunity to better document "today's" climate, which would reduce the confidence of scientific evaluations/estimations of future climate changes. The data describing each day are a "limited edition", not likely to be reproduced exactly again!

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Question: (Asked to all witnesses) What kinds of things would better computing power allow climate scientists do that cannot be done now? What are the barriers to improving our computing capabilities? How might the U.S. climate modeling community make more efficient use of its available resources?

Answer:

As with the first question above, the National Research Council recently has carried out an explicit study of this question: "Capacity of U.S. Modeling to Support Climate Change Assessment Activities", National Research Council, U.S. National Academy of Sciences, (1998). This report notes that, at the time, the U.S. lags behind other countries in its ability to model long-term climate change. If computing capabilities were improved, it would enable U.S. scientists to more accurately predict future climate and to most effectively advance understanding of the underlying issues pertaining to climate variability and change. Researchers could perform coupled atmosphere-ocean climate change scenario simulations at the spatial resolution relevant to certain national policy decisions (e.g., finer than 500 km × 800 km). Benefits include a clearer picture of the magnitude and impact of climate change, and a better ability for decision-makers to formulate policies that will be consistent with national objectives. The NRC study also noted that there were barriers to improved computing/more efficient use of available resources: (i) the absence of a national strategy, (ii) the existence of trade-policy barriers, and (iii) the lack of a coordinated funding of human resources.

In terms of the computer/model needs that are associated with policy-relevant information gaps, the most important are, in my view, the following:

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Access to greater computing power. *Infrastructure Focus:* The picture is clear. Improvements in computing power over the past decade have led to better predictions because they enable analyses to be made at a "finer scale". For example, important processes lie at smaller time/space scales, e.g., precipitation. Therefore, for a balanced monitoring, processes, and modeling program (which is the required triad for improved prediction), investment in the growth in computing power is a necessary ingredient. Higher spatial or temporal resolution that would result from greater computing power would, for example, benefit meeting the needs described in the next two bullets. *Payoff:* Having the needed tools in the toolbox to match the growth in understanding.

Attributing the vertical profiles of atmospheric temperatures and other variables. *Research Foci:* Specific features of the vertical profile of temperature (e.g., the difference between satellite-derived and surface-based temperatures in the tropics) do not have a full explanation and have been an attention-generating issue. More generally, the vertical profiles of variables are a powerful diagnostic of the level of understanding of many processes (e.g., storm-driven transport). A coordinated observational program (with diverse platforms) and diagnostic model likely has low-lying fruit (e.g., the point above). *Payoff:* Assessment of the global understanding, not just in global averages and not just near the surface, but also in the "vertical world", will add a new and valuable dimension to confidence levels.

Conceptually integrating the components of the coupled ocean-atmosphere system. *Research Foci:* Progress has occurred in the model simulations of global and longer-term changes (e.g., the past century) and in the simulation of smaller-spatial scale and shorter-term variations (El Niño), as verified by comparison to observations. A substantial part of this progress was in a better conceptual understanding of the coupled system (e.g., atmosphere-ocean). A renewed focus of such coupling could reveal how global, long-term increases in climate-related factors will reveal itself, not just in global-average changes, but also in supra-regional and regional patterns and in the change in the variability of climate patterns. *Payoff:* Information on how natural phenomena and climate patterns, such as El Niño (whose societal impacts are usefully being characterized), could change (or not change) with further increases in climate-related "greenhouse" gases would add impact-quantified, decision-relevant information.

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Question: (Asked to all witnesses) How many data points from the ocean were incorporated into the IPCC's final analysis and do you believe it to be a sufficient number? Why or why not? How do the number of data points in the ocean compare to the number of data points on land?

Answer:

The data records that are used by the scientific community (and hence used in the assessment of the IPCC) are the following:

For sea-surface temperature trends: Over 80 million observations from 1870 to the present time were used from the United Kingdom Main Marine Data bank, the United States Comprehensive Ocean Atmosphere Data Set, and recent information telecommunicated from ships and buoys from the World Weather Watch. As noted in the assessment, there are some regions of missing/unavailable data. Many historical in-situ marine data still remain to be digitized and incorporated into the database, to improve coverage and reduce the uncertainties in estimates of marine climatic variations.

For land-surface temperature trends: The number of temperature observations over land that are used to calculate trends is approximately 250 million. These data come from the numerous stations worldwide at which temperature is measured. The trend analyses have researched and incorporated biases from calibration changes and from such local effects as "urban heat island". For the Southern Hemisphere, land temperature data actually represent a very small observed area of the hemisphere (while the sea surface temperature data, though sparse, are generally considerably more widespread).

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The question of sufficiency of observations relates to the level of confidence associated with the conclusion drawn from the set of data. Naturally, more observations afford the opportunity of higher confidence. The researchers who prepared IPCC Chapter 2, "Observed Climate Variability and Change", took the number of observations and the locations sampled into account in framing the uncertainty of the trends that they cited. For example, they cite: "The global average surface temperature (the average of near surface air temperature over land, and sea surface temperature) has increased since 1861. Over the 20th century the increase has been 0.61B0.2 degrees Celsius [at the 95% confidence level]". The data were adequate to discern a difference in the warming trends over land and over sea, with the former being larger than the latter. The authors noted the improvements in the data set and analyses since the 1995 IPCC conclusions (for example, an independent test of the corrections of time-dependent biases in the sea surface temperature data). They also pointed out the shortcomings that prevent a higher confidence level associated with trends (for example, the relative sparseness of Southern Hemisphere data).

Question: (Asked to all witnesses) Would an integrated ocean observing system be useful to climate modelers and result in more accurate models? What physical, human, and fiscal resources are required to build and maintain a multi-decadal climate monitoring network that, 50 years from the present, can with the highest degree of confidence answer the question: "How has the climate changed?"

Answer:

A good example of the needed ocean observing system is the "Argo array". Argo, a broad-scale global array of temperature/salinity profiling floats, is now planned as a major component of an ocean observing system. Temperature and salinity of the upper 2000 meters of the ocean will be measured by the array of 3000 free-drifting profiling floats. Conceptually, Argo builds on the existing upper-ocean thermal networks, extending their spatial and temporal coverage, depth range and accuracy, and enhancing them through addition of salinity and velocity measurements. Argo will continuously monitor the climate state of the ocean, with all data being relayed and made publicly available within hours after collection. For the first time, the physical state of the upper ocean will be systematically measured and assimilated in near real-time.

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Completion of the planned-for 3000 floats will be important to the achievement of several scientific advances:

(1) improvements in the predictability of season-to-decadal climate variability;

(2) quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability; and

(3) provision of data inputs for the initialization and evaluation of ocean and coupled ocean-atmosphere forecast models.

The Argo array is part of the Global Climate Observing System/Global Ocean Observing System (GCOS/GOOS) and part of the Climate Variability and Predictability Experiment (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE).

In addition to the Argo observing system mentioned above, there are specific ocean observations that are important to a better understanding the role of the oceans in the climate system and to better characterize the key climate-system processes that currently limit prediction and hence decision-making associated with climate change. A few of the most pressing ones are noted below. In addition, to address the Committee's question about how to gain the highest degree of confidence in answering the question about how climate has changed, the answer below also describes the corresponding needs associated with the air-land-surface interface.

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Clarifying what are the "choke points" of the lame-scale oceanic circulation. *Research Foci:* Models and paleo-climate studies indicate that the large-scale, density-driven ("thermohaline") oceanic circulation plays an important role in long-term atmospheric climate. In addition to periodic variability, this circulation may play an important role in abrupt climate change, a possibility that has attracted considerable attention. Since the thermohaline circulation is global, a cost-effective and efficient method of monitoring this component of oceanic circulation is needed. Continuous measurements of water mass properties (e.g., temperature, salinity, oxygen, etc.) and transport at a limited number of locations can provide these data. Specifically, flow through the passages south of Africa and South America represent such chokepoints. In addition, flows out of the Arctic and

Mediterranean are also important. Additional information about narrow-channel flows (e.g., between Iceland and Greenland) and boundary (i.e., near land) flows would substantially improve the understanding of this circulation and its changes. *Payoffs:* Data and analyses at these choke-points will provide (i) information on the intensity of the thermohaline oceanic circulation and early warning signs for any abrupt climate change and (ii) improved predictive understanding of the role of the thermohaline circulation in the climate system. Hence, speculation would be narrowed, and quantitative simulations of potential change (of lack of change) of this major climate feature would provide important information relevant to society.

Improved observations of climatically important gas exchanges between atmosphere and ocean. *Research Foci:* Surface atmospheric data (wind, heat flux, etc.) are regularly collected from Voluntary Observing Ships (VOS), fixed buoys, and surface drifters, for example. Techniques for measuring gas exchange via these types of platforms are also needed. For example, CO exchange between ocean and atmosphere is an important component of the global cycling of carbon between oceans and atmosphere. In addition, detailed water-column measurements made in the past should be continually revisited (on a five to ten-year cycle) to determine the total water column inventory of heat, salt, and climatically important gases. Previous studies have shown that the ocean is warming, but the data used in these studies will not be continuously available in the future. Only some ten transects will be needed globally to provide this information. *Payoffs:* These data will (i) help ensure that climate signals can be distinguished from instrument signals, (ii) provide continuous calibration/validation observations for satellite-based estimates of gas exchange processes; (iii) help provide the information needed to attribute the cause of climate signals; and (iv) help determine the ocean's role in climate change and to attribute this change to natural and/or anthropogenic causes.

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Characterizing land-surface/biosphere/atmosphere interactions. *Research foci:* Land-surface changes provide important feedbacks in the climate system since climate changes influence the state of the land surface (e.g., soil moisture, reflectivity, and vegetation cover). Requiring better characterization are, for example, large-scale deforestation and reforestation, including their impact on the hydrological (water) cycles. *Payoff:* Being able to incorporate such feedbacks better into climate models will allow the past rich historical and the growing paleo data base to test effectiveness of the needed sub-global predictive skills.

Understanding abrupt climate changes: When and why? *Research foci:* Paleoclimate data reveal that relatively abrupt and sustained climatic shifts have occurred in the past. The formation of the Sahara Desert about 5,500 years ago is an example of such an abrupt change (perhaps from a non-linear change in land cover, which relates to the preceding bullet). Focusing paleoclimatic and diagnostic modeling on such events could better identify threshold mechanisms, such as those that could be related to abrupt shifts in the oceanic circulation (as noted in the first bullet in the above section). *Payoffs:* It would be enormously important and relevant to decision-making to be able to assess quantitatively the likelihood of an abrupt climate shift during the coming century, since current climate models are simulating a rate of warming of global temperatures without precedent during at least the last 10,000 years.

Characterizing water vapor and clouds. *Research Foci:* The water-vapor feedback process amplifies (by a factor of two) the greenhouse role of all other greenhouse gases. Further, clouds are a key factor in the albedo (i.e., reflectivity) of the planet, as well as many "feedback" processes. Focused remote-sensing and in-situ studies with new techniques could improve this understanding substantially, when combined with diagnostic interpretation of the challengingly-large spatial and temporal variability. *Payoffs:* Understanding these processes would address what is probably the largest modeling deficiency that contributes to the wide uncertainty range of simulated temperature increases that would be expected for a given future emission scenario. This research would address the fundamental need for the "scientific" uncertainty associated with any particular option (scenario) to be less than the difference between the outcomes of various different options (i.e., being able to demonstrate that there is a real benefit).

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Question: (Asked to all witnesses) The recent Kyoto negotiations at the Hague were stymied in large part due to disagreements over how efficient plants are at tying up carbon from the atmosphere. Are the current carbon cycle programs sufficient to obtain the understanding we need so that we can make appropriate policy decisions?

Answer:

Indeed, discussions focusing on altering greenhouse gas emissions are confronted with information gaps that limit the ability to estimate better the future atmospheric concentrations/climate-forcing of atmospheric constituents. Carbon dioxide is a major greenhouse gas, and the first point below addresses associated needs for scientific understanding on that topic. My answer also includes important information regarding "other" greenhouse gases that could potentially play a role in facilitating the broad discussions that occur in policy negotiations. Two of the most-immediate policy-relevant research needs are the following:

Better parameterization of the carbon cycle. *Research foci:* While the source of human-influenced carbon emissions is relatively well quantified, the fate and time history of carbon emissions are not as well known. Better information on the annual/decadal terrestrial processes involved (e.g., biospheric uptake/release) is required for defensible options for carbon management. Similarly, characterization of processes involved in the large carbon-uptake, long-term storage role of the oceans is a key to better establishing the fraction of emitted carbon that remains in the atmosphere in the decadal/century time frame. *Payoffs:* Having a better quantitative model of the carbon cycle, including how climate change will influence it, will yield more credible simulations of future CO abundance (hence, radiative forcing) for specified choices on emissions ("What change in radiative forcing results from what emission changes?").

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Quantify radiative roles, trends, and variations of the shorter-lived greenhouse gases and aerosols. *Research Foci:* Ozone in the lower atmosphere (troposphere) and aerosols (fine airborne particles) play unique (but poorly quantified) roles in climate change. Both cause regional radiative forcing, but of opposite sign (warming for ozone, cooling for sulfur-containing aerosols, and warming for carbon-containing aerosols), which is very unlike the global distribution of carbon dioxide. Further, these constituents have short atmospheric residence times, and therefore afford the means for changing climate-related driving factors in the near term (unlike the slow decadal response associated with CO). Further, tropospheric ozone and aerosols are associated with other environmental issues (e.g., poor air quality). Major information gaps could be addressed by process and modeling studies that better link emissions to global distributions and to radiative forcing patterns, both past and future. *Payoffs:* In short, to improve the now-weak quantitative knowledge of the shorter-lived constituents would (i) open additional quantified options for changing climate-related driving factors, (ii) provide information on how choices associated with one issue would influence another issue, and (iii) substantially improve the level of confidence in model predictions of, say, temperature increase over this century.

Question: (Asked to all witnesses) The USGCRP is a collaborative multi-agency initiative. How can global climate research be strengthened given the dispersed nature of the initiative? Does the USGCRP umbrella of agencies have a coordinated approach for prioritizing, from a national perspective, their climate modeling research and assessment efforts?

Answer:

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The U.S. Global Change Research Program is a multi-Agency effort, with the inherent advantages and disadvantages of such diversity. The Program is currently establishing its pathways and procedures for its second decade by developing a ten-year plan that focuses on the highest priority research issues.

Question: (Asked to all witnesses) Are human and fiscal resources allocated effectively to address the above mentioned priorities? Are students being trained to fill either the scientific research positions or the niches of computational science and software engineering required for a successful high-end climate computing capability?

Answer:

Current budgets effectively allocate resources for climate change research priorities. The President's Global Climate Change Initiative will set priorities for additional investments in climate change research. The initiative is planned to fully fund high-priority areas for climate change science over the next five years. Regarding students, the academic colleagues that testified with me are far better informed about the educational needs and how well they are being met.

Question: (Directed to Dr. Albritton) Is it possible that the warming we're seeing is part of some natural fluctuations, some kind of "noise" if you will, in the system?

Answer:

In Chapter 12 ("Detection of Climate Change and Attribution of Causes") of the IPCC, the researchers assessed this likelihood raised in the question above. The assessment compared the observed global-average surface temperature changes to those simulated by climate models for three Cases: (a) natural variation, (b) anthropogenic climate-change forcing, and (c) the combination of natural variation and anthropogenic forcing. As shown in Figure 4 of the IPCC Summary For Policymakers, the best match was Case (c). The mismatch over the past few decades with natural variation alone (Case a) is easily discernible. This and several related considerations led to the conclusion: "In light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the past 50 years is likely to have been due to the increase in greenhouse gas concentrations" (p. 10, IPCC Summary For Policymakers). The IPCC researchers used the word "likely" to represent a judgmental estimate of confidence level of a 66–90% chance of being correct (p. 2, Footnote 7, IPCC Summary For Policymakers).

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Question: (Directed to Dr. Albritton) If a scientist wanted to "prove" that the warming we've seen is, in fact, just part of the background noise and not caused by people, what kind of proof would he need? And is anyone looking for that kind of proof?

Answer:

In the approach outlined in the last question regarding natural fluctuations, a study would have to demonstrate that an hypothesized natural process, when added to a simulation of surface temperature, matched the observed temperature record, to a specified confidence level. Several such natural mechanisms (e.g., changes in total solar irradiance, solar ultraviolet radiation, cosmic rays and clouds, and volcanic emissions) have been hypothesized. As the IPCC researchers assessed, they have not produced reliable simulations of the warming of the past 50 years. It was noted that solar irradiance changes may have contributed to the observed warming in the first half of the 20th century. Sulfate particles from the emissions of explosive volcanoes (e.g., Mt. Pinatubo in 1991) have been observed to cause a small cooling of the climate system for a few years until the particles have settled out of the atmosphere. No such test has found a natural process that could simulate the warming of the past 50 years.

Hypotheses of potential new climate-relevant processes, both natural and human-influenced, will no doubt continue to be put forward and tested, since that is the scientific process by which understanding is improved.

Question: (Directed to Dr. Albritton) Would you say that the IPCC's findings "prove" *that climate change is being caused by human activities? If not, what scientific "proof" would be required, and what do you think is necessary to get that proof?*

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Answer:

Scientific insights are described as a conclusion *with a stated confidence level.* As noted under Question (A) above, the researchers of the detection/attribution chapter (Chapter 12) of the IPCC placed a 66–90% confidence level in the attribution that most of the warming observed over the past 50 years is due to human activities.

As the three major assessments by IPCC researchers over the past decade indicate, the confidence level associated with the detection of a climate change and the attribution to human influences has increased over the last 10 years. The reasons are several fold: a longer and more closely scrutinized temperature record, better simulation of natural climate variations, and new estimates of the climate response to natural and human-influence climate forcings. Further, the magnitude of the greenhouse-gas forcing of climate-altering radiation increases each year; therefore, the ease of detection increases with time.

For reference, the earlier and current attribution conclusions of IPCC researchers are:

IPCC (1990): "The size of this warming [0.3–0.6 degrees Celsius over the last 100 years] is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. . .. The unequivocal detection of the enhanced greenhouse effect is not likely for a decade or more."

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IPCC (1995): "The balance of evidence suggests a discernible human influence on global climate."

IPCC (2001): "In light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the past 50 years is likely [i.e., 66–90% confidence level] to have been due to the increase in greenhouse gas concentrations."

How can the understanding of climate changes and their causes be improved, that is, a statement with yet-higher confidence? The IPCC researchers identified the source of remaining uncertainties in detection and attribution. As noted, many of the explicit near-term research needs summarized above address improvements in detection and attribution (e.g., discrepancies between the vertical profile of temperature change in the lower atmosphere seen in observations and simulated by climate models).

PREPARED STATEMENT OF BERRIEN MOORE III

I. INTRODUCTION

There has been encouraging progress over the past decade. We understand better the coupling of the atmosphere and ocean. Significant steps have been taken in linking the atmosphere and the terrestrial systems, though the focus tends to be on water-energy and the biosphere with fixed vegetation patterns. There is also encouraging progress in developing integrated-assessment models that couple economic activity, with associated emissions and impacts, with models of the biogeochemical and climate systems. This work has yielded preliminary insights into system behavior and key policy-relevant uncertainties.

The challenges are significant, but the record of progress suggests that within the next decade the scientific community will develop fully coupled dynamical (prognostic) models of the full Earth system (e.g., the coupled physical climate, biogeochemical, human subsystems) that can be employed on multi-decadal time scales and at spatial scales relevant to strategic impact assessment. Future models should certainly advance in completeness and sophistication; however, the key will be to demonstrate some degree of prognostic skill. The strategy will be to couple the biogeochemical-physical climate system to representations of key aspects of the human system, and then to develop more coherent scenarios of human actions in the context of feedbacks from the biogeochemical-physical climate system.

Developing these coupled models is an important step. From the perspective of understanding the Earth system, determining the nature of the link between the biogeochemical system and the physical-climate system represents a fundamental scientific goal. Present understanding is incomplete, and a successful attack will require extensive interdisciplinary collaboration. It will also require global data that clearly documents the state of the system and how that state is changing as well as observations to illuminate more clearly important processes.

II. THE CLIMATE SYSTEM

II.1 Overview

Models of physical processes in the ocean and atmosphere provide much of our current understanding of future climate change. They incorporate the contributions of atmospheric dynamics and thermodynamics through the methods of computational fluid dynamics. This approach was initially developed in the 1950s to provide an objective numerical approach to weather prediction. It is sometimes forgotten that the early development of "supercomputers" at that time was motivated in large part by the need to solve this problem. In the 1960s, versions of these weather prediction models were developed to study the "general circulation" of the atmosphere, i.e., the physical statistics of weather systems satisfying requirements of conservation of mass, momentum, and energy. To obtain realistic simulations, it was found necessary to include additional energy sources and sinks: in particular, energy exchanges with the surface and moist atmospheric processes with the attendant latent heat release and radiative heat inputs.

Development of models for the general circulation of the ocean started later, but has proceeded in a similar manner. Models that deal with the physics of the oceans have been developed and linked to models of the atmospheric system. Within ocean models, the inclusion of biogeochemical interactions has begun, with a focus upon the carbon cycle. Modelling of the biological system, however, has been more challenging, and it has been only of late that primitive ecosystem models have been incorporated in global general circulation ocean models. Even though progress has been significant, much remains to be done. Eddy-resolving ocean models with chemistry and biology need to be tested and validated in a transient mode, and the prognostic aspects of marine ecosystems including nutrient dynamics need greater attention at basin and global scales.

Model development for the ocean and atmosphere has had a fundamental theoretical advantage: It is based on the firmly established hydrodynamic equations. At present there is less theoretical basis for a "first principles" development of the dynamical behavior of the terrestrial system. There is a need to develop a fundamental methodology to describe this very heterogeneous and complex system. For the moment, it is necessary to rely heavily upon parameterisations and empirical relationships. Such reliance is data intensive and hence independent validation of terrestrial system models is problematical. In spite of these difficulties, a coordinated strategy has been developed to improve estimates of terrestrial primary productivity and respiration by means of measurement and modelling. The strategy has begun to yield dividends. Techniques from statistical mechanics have been wedded with biogeochemistry and population ecology yielding new vegetation dynamic models.

Expanded efforts are needed in these domain-specific models. In the ocean, we need to consider better the controls on thermohaline circulation, on potential changes in biological productivity, and on the overall stability of the ocean circulation system. Within terrestrial systems the question of the carbon sink-source pattern is central: What is it and how might it change? Connected to this question is the continued development of dynamic vegetation models, which treat competitive processes within terrestrial ecosystems and their response to multiple stresses. And for the atmosphere, a central issue is the role of clouds. Also, there is a corresponding nonlinearity associated with change in the distribution and extend of sea ice. Further increased efforts will be needed in linking terrestrial ecosystems with the atmosphere, the land to the ocean, the ocean (and its ecosystems) with the atmosphere, the chemistry of the atmosphere with the physics of the atmosphere, and finally linking the human system to them all. Such models will also need to be able to highlight different regions with increased spatial and temporal detail.

Models, however, depend upon high quality data. Data allow hypotheses about processes and their linkages to be rejected or to be given increased consideration. Giving formal (e.g., quantitative) expression to processes is at the heart of the scientific enterprise. Such expressions reflect our knowledge and form the basis for models.

Systematic global observations are an essential underpinning of research to improve understanding of the climate system. Unfortunately, there continues to be justifiable concerns about the loss of monitoring of climate parameters and deterioration of coverage. There is a basic need for more observations with better coverage, higher accuracy, and with increased availability. On a positive note, there is an emerging plan for the implementation of global observing systems: the Global Climate Observing System, the Global Ocean Observing System, and the Global Terrestrial Observing System. However plans in themselves do not produce data, and data that are not accessible are of limited value. The issue of data remains central for progress.

II.2 Predictability in a chaotic system

The climate system is particularly challenging since it is known that components in the system are inherently chaotic; there are feedbacks that potentially could switch sign, and there are central processes that affect the system in a complicated, nonlinear manner. These complex, chaotic, nonlinear dynamics are an inherent aspect of the climate system. There is the possibility for future unexpected, large and rapid climate system changes (as have occurred in the past), and such changes are, by their nature, difficult to predict. Such changes arise from the nonlinear, chaotic nature of the climate system. Reducing uncertainty in climate projections requires a better understanding of these nonlinear processes that give rise to thresholds that are present in the climate system.

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This challenge of developing predictive capability is central, but this development is quite challenging when predictive capability is sought for a system that is chaotic, that has significant nonlinearities, and that has widely varying time constants. And within prognostic investigations of such a complex system, the issue of predicting extreme events presents a particularly vexing yet important problem.

Extreme events are, almost by definition, of particular importance to human society. It is often stated that the impacts of climate change will be felt through changes in extremes because they stress our present day adaptations to climate variability. Consequently, the importance of understanding potential extreme events is first order. To date, it is not yet clear that we have extensive capability in predicting extreme events. The evidence is simply mixed, and data continue to be lacking to make conclusive cases.

There appears to be some consistent patterns with increased CO with respect to changes in variability: a) the Pacific climate base state could be a more El Niño-like state and b) an enhanced variability in the daily precipitation in the Asian summer monsoon with increased precipitation intensity. More generally, the intensification of the hydrological cycle with increased CO is a robust conclusion. For possible changes in extreme weather and climate events, the most robust conclusions appear to be: a) an increased probability of extreme warm days and decreased probability of extreme cold days and b) an increased chance of drought for midcontinental areas during summer with increasing CO.

The evaluation of many types of extreme events is made difficult because of issues of scale. Damaging extreme events are often at small temporal and spatial scales. Intense, short duration events are not well represented (or not represented at all) in model simulated climates. There is still a mismatch between the scale of climate models and the finer scales appropriate for surface hydrology. This is particularly problematical for impact studies. For droughts there is a basic issue of predictability; drought prediction is difficult regardless of scale.

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An important issue is the adequacy of data needed to attack the question of changes in extreme events. We are unfortunately short of data for the quantitative assessment of extremes on the global scale in the observed climate.

Setting aside the important issue of predicting extreme events, there remains the challenge of prediction within the climate system per se given its complex, nonlinear, chaotic nature. Is there evidence of the possibility of prediction? Interestingly, there appear to be coherent modes of behavior that not only support a sense of optimism in attacking the prediction problem, but also these modes may offer measurable prediction targets that can be used as benchmarks for evaluating our understanding of the climate system. In addition, predicting these modes represent valuable contributions in themselves.

Evaluating the prognostic skill of a model and understanding the characteristics of this skill are clearly important objectives. There are also are the paired challenges of capturing (predicting) "natural" variability of climate as well as the emerging anthropogenically forced climate signal. This dual challenge is distinctively climatic in nature, and whereas the longer-term character of climate projections is unavoidable and problematic, the intraseasonal to interdecadal modes of climate variability (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation) offer opportunities to test prognostic climate skill. Here, some predictive skill for the climate system appears to exist on longer time scales. One example is the ocean-atmosphere phenomenon of El Niño-Southern Oscillation (ENSO). This skill has been advanced and more clearly demonstrated over the past decade, and this progress and demonstration are important. Such demonstrations and the insights gained in developing and making prognostic statements on climate modes frame an important area for further work.

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Finally, there is the need to have access to significantly greater computing resources and the need to apply computing resources more wisely.

There is a natural tendency to produce models at finer spatial scales that include both a wider array of processes and more refined descriptions. Higher resolution can lead to better simulations of atmospheric dynamics and hydrology, less diffusive oceanic simulations, and improved representation of topography. In the atmosphere, fine scale topography is particularly important for resolving small-scale precipitation patterns. In the ocean, bottom topography is very important for the various boundary flows. The use of higher oceanic resolution also improves the simulation of internal variability such as ENSO. However, in spite of the use of higher resolution, important climatic processes still are not resolved by the model's grid necessitating the continued use of subgrid scale parameterisations.

Underlying this issue of scale and detail is an important tension. As the spatial and process detail in a model is increased, the required computing resources increase, often significantly. Models with less detail may miss important nonlinear dynamics and feedbacks that effect model results significantly, and yet simpler models may be more appropriate to generating the needed statistics. The issue of spatial detail is intertwined with the representation of the physical (and other) processes, and hence the need for a balance between level of process detail and spatial detail. These tensions must be recognized forthrightly, and strategies must be devised to use the available computing resources wisely. Analyses to determine the benefits of finer scale and increased resolution need to be careful considered. These considerations must also recognize that the potential predictive capability will be unavoidably statistical, and hence it must be produced with statistically relevant information. This implies that a variety of integrations (and models) must be used to produce an ensemble of climate states. Climate states are defined in terms of averages and statistical quantities applying over a period typically of decades.

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In sum, a strategy must recognize what is possible. In climate research and modelling, we should recognize that we are dealing with a coupled nonlinear chaotic system, and therefore that the long-term prediction of future climate states is not possible. The most we can expect to achieve is the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. This reduces climate change to the discernment of significant differences in the statistics of such ensembles. The generation of such model ensembles will require the dedication of greatly increased computer resources and the application of new methods of model diagnosis. Addressing adequately the statistical nature of climate is computationally intensive, but such statistical information is essential.

II.3 Key subsystems and phenomena in the physical-climate system

Central to the climate system are the coupled dynamics of the atmosphere-ocean-terrestrial system, the physical processes associated with the energy and water cycles and the associated biological and chemical processes controlling the biogeochemical cycles, particularly carbon and nitrogen. The atmosphere plays a unique role in the climate system since on a zeroth order basis it sets the radiative forcing. Specific subsystems that are important and yet still poorly understood are clouds and sea ice; the thermohaline ocean circulation is a fundamentally important phenomenon that needs to be known better, and underlying these subsystems and phenomena are the still ill-understood nonlinear process of advection (large scale) and convection (small scale) of dynamical and thermodynamical oceanic and atmospheric quantities. These subsystems, phenomena, and processes are important and merit increased attention to improve prognostic capabilities generally.

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II.3.1 Clouds

The role of clouds in the climate system continues to challenge the modelling of climate. It is generally accepted that the net effect of clouds on the radiative balance of the planet is negative and has an average magnitude of about 10–20 Wm–2. This balance consists of a short-wave cooling (the albedo effect) of about 40–50 Wm–2 and a long-wave warming of about 30 Wm–2. Unfortunately, the size of the uncertainties in this budget is large when compared to the expected anthropogenic greenhouse forcing. Although we know that the overall net effect of clouds on the radiative balance is slightly negative, we do not know the sign of cloud feedback with respect to the increase of greenhouse gases, and it may vary with the region. In fact, the basic issue of the nature of the future cloud feedback is not clear. Will it remain negative? If the planet warms, then it is plausible that evaporation will increase which probably implies that liquid water content will increase but the volume of clouds may not. What will be the effect and how will the effects be distributed in time and space? See Meehl and Washington, 1995.

Finally, the problems associated with how to treat clouds within the climate system are linked to problems associated with aerosols. Current model treatments of climate forcing from aerosols predict effects that are not always consistent with the past climate record. A major challenge is to develop and validate the treatments of the microphysics of clouds and their interactions with aerosols on the scale of a general circulation model grid. A second major challenge is to develop an understanding of the carbon components of the aerosol system. Meeting this challenge requires that we both develop data for a mechanistic understanding of carbonaceous aerosol effects on clouds as well as an understanding of the magnitude of the anthropogenic and natural components of the carbonaceous aerosol system.

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The importance of clouds was summarised by the 1996 Working Group 1 report of the IPCC: "The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle" (Kattenberg et al., 1996, p345). And yet, the single greatest source of uncertainty in the estimates of the climate sensitivity continues to be clouds. Over the last decade, there have been a number of improvements in the simulation of both the cloud distribution and in the radiative properties of clouds. The simulation of cloud distribution has improved as the overall simulation of the atmospheric models has improved. In addition, the cloud sub-component models used in the coupled models have become more realistic Also, our understanding of the radiative properties of clouds and their effects on climate sensitivity have improved. And yet in the Third Assessment Report of Working Group 1 of the IPCC, it will be stated (Chapter 7) that, "In spite of these improvements, there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate change simulations."

Handling the physics and/or the parameterisation of clouds in climate models remains a central difficulty. There is a needed for increased observations. J. Mitchell highlighted the challenge in a recent paper at the WCRP Workshop on Cloud Properties and Cloud feedbacks in Large-scale Models where he states that "Reducing the uncertainty in cloud-climate feedbacks is one of the toughest challenges facing atmospheric physicists." (Mitchell, 2000)

Cloud modelling is a particularly challenging scientific problem because it involves processes covering a very wide range of space and time scales. For example, cloud systems extending over thousands of kilometres to cloud droplets and aerosols of microscopic size are all important components of the climate system. The time scales of interest can range from hundreds of years (e.g., future equilibrium climates) to fractions of a second (e.g., droplet collisions). This is not to say that all cloud micro-physics must be included in modelling cloud formation and cloud properties, but the demarcation between what must be included and what can be parameterised remains unclear. Clarifying this demarcation and improving both the resulting phenomenological characterisations and parameterisations will depend critically on improved global observations of clouds. Of particular importance are observations of cloud structure and distribution against natural patterns of climate variability (e.g., ENSO). Complementing the broad climatologies will be important observations of cloud ice water and liquid water content, radiative heating and optical depth profiles, and precipitation occurrence and cloud geometry.

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The recently approved CloudSat and PICCASO missions, which will fly in formation with the NASA EOS PM (the Aqua Mission), will provide valuable profiles of cloud ice and liquid content, optical depth, clod type, and aerosol properties. These observations combined with wider swath radiometric data from EOS PM sensors will provide a rich new source of information about the properties of clouds (Stephens et al., 2000).

And yet, this question of cloud feedback remains open, and it is not clear how it will be answered. Given that the current generation of global climate models represents the Earth in terms of gridpoints spaced roughly two hundred kilometres apart, many features observed on smaller scales, such as individual cloud systems and cloud geometry, are not explicitly resolved. Without question, the strategy will for attacking the feedback question will involve comparison of model simulations with appropriate observations on global or local scales. The interplay of observation and models, again, will be the key for progress. Mitchell (Mitchell, 2000) states this clearly, "Unless there are stronger links between those making observations and those using climate models, then there is little chance of a reduction in the uncertainty in cloud feedback in the next twenty years." This will be echoed in Chapter 7 of the Third Assessment Report of Working Group 1 of the IPCC, "A straightforward approach of model validation is not sufficient to constrain efficiently the models and a more dedicated approach is needed. It should be favoured by a larger availability of satellite measurements."

II.3.2 Thermohaline circulation

In a few model calculations, a large rate of increase in the radiative forcing of the planet, such as a major increase in the concentration of atmospheric carbon dioxide, is enough to cause the ocean's global thermohaline circulation almost to disappear, though in some experiments it reappears given sufficiently long integration times. This circulation is important because in the present climate it is responsible for a large portion of the heat transport from the tropics to higher latitudes, and it plays an important role in the oceanic uptake of carbon dioxide. Paleo-oceanographic investigations suggest that aspects of longer-term climate change are associated with changes in the ocean's thermohaline circulation. We need appropriate observations of the thermohaline circulation, and its natural variations, to compare with model simulations.

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The coming decade will be important for ocean circulation in the context of climate. A particularly exciting development is the assimilation of synoptic ocean observations (e.g., TOPEX-Poseidon and ARGO) into ocean general circulation models. Key questions, such as how well do the ocean models capture the inferred heat flux or tracer distributions are central to the use of these models in climate studies. The effort of comparing models with data, as the direct path for model rejection and model improvement, is central to increasing our understanding of the system.

II.3.3 Arctic sea ice

There is increasing evidence that there is a decline in extent and thickness of Arctic sea ice in the summer that appears to be connected with the observed recent Arctic warming (For a general discussion on the role sea ice in the climate system as well as recent advances in modelling sea ice see Chapter 2, 7 and 8 in the soon to be published Third Assessment Report of Working Group 1 of the IPCC; see also Randall et al., 1998).

It is not known whether these changes reflect anthropogenic warming transmitted either from the atmosphere or the ocean or whether they mostly reflect a major mode of multi-decadal variability. Some of this pattern of warming has been attributed to recent trends in the Arctic Oscillation; however, how the anthropogenic signal is imprinted on the natural patterns of climate variability remains a central question. What does seem clear is that the changes in Arctic sea ice are significant, and there is a positive feedback that could be triggered by declines in sea ice extent through changes in the planetary albedo. If the Arctic shifted from being a bright summer object to a less bright summer object, then this would be an important positive feedback on a warming pattern.

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In addition to these recently available observations, there have been several models (e.g., CSIRO—Gordon and O'Farrell 1997; DOE PCM—Washington et al. 1999; NCAR

CSM—Weatherly et al, 1998) that have improved their sea ice representation over the past five years. These improvements include simulation of open water within the ice pack, snow cover upon the ice, and sea ice dynamics. The incorporation of sophisticated sea ice components in climate models provides a framework for testing and calibrating these models with observations. Further, as the formulation of sea ice dynamics becomes more realistic, the validity of spatial patterns of the simulated wind stress over the polar oceans is becoming an issue in climate simulations. Hence, improvements, such as the above-mentioned data, in the observational database will become increasingly relevant to climate model development.

In order to improve model representations and validation, it will be essential to enhance the observations over the arctic of ocean, atmosphere, and sea ice state variables. This will help provide more reliable projections for a region of the world where significant changes are expected. The refinement of sea ice models along with enhanced observations reduces the uncertainty associated with ice processes. This progress is important, and efforts are needed to expand upon it and as stated to improve significantly the observational basis.

II.4 The global carbon cycle

From measurements of air trapped in ice-cores and from direct measurements of the atmosphere, we know that in the past 200 years the abundance of CO in the atmosphere has increased by over 30% (i.e., from a concentration of 280 parts-per-million by volume (ppmv) in 1700 to nearly 370 ppmv in 2000). We also know that the concentration was relatively constant (roughly within +/–10 ppmv of 275) for more than 1000 years prior to the human-induced rapid increase in atmospheric carbon dioxide.

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But looking further back in time, we find an extraordinarily regular record of change.

The Vostok core captures a remarkable and intriguing signal of the periodicity of interglacial and glacial climate periods in step with the transfer of significant pools of carbon from the land (most likely through the atmosphere) to the ocean and then the recovery of terrestrial carbon back from the ocean. The repeated pattern of a 100–120 ppmv decline in atmospheric CO from an interglacial value of 280–300 ppmv to a 180 ppmv floor and then the rapid recovery as the planet exits glaciation suggests a tightly governed control system. There is a similar CH cycle between 320–350 ppbv (parts per billion by volume) and 650–770 ppbv. What begs explanation are not just the linked periodicity of carbon and glaciation, but also the apparent consistent limits on the cycles over the period.

Today's atmosphere, imprinted with the fossil fuel CO signal, stands at nearly 90–70 ppmv above the previous interglacial maximum of 280–300 ppmv. The current methane value is even further (percentage-wise) from its previous interglacial high values. In essence, carbon has been moved from a relatively immobile pool (in fossil fuel reserves) in the slow carbon cycle to the relatively mobile pool (the atmosphere) in the fast carbon cycle, and the ocean, terrestrial vegetation and soils have yet to equilibrate with this "rapidly" changing concentration of carbon dioxide in the atmosphere.

Given this remarkable and unprecedented history one cannot help but wonder about the characteristics of the carbon cycle in the future.

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To understand better the global carbon cycle, two themes are clear: 1) there is a need for global observations that can contribute significantly to determining the sources and sinks of carbon and 2) there is a need for fundamental work on critical biological processes and their interaction with the physical system.

There is also a range of areas where present-day biogeochemistry modelling is not only in need of additional data, but is also crucially limited by insufficient understanding at the level of physical or biological processes. Clarifying these process and their controls is central to a better understanding of the global carbon cycle.

II.4.1 The marine carbon system

The marine carbon cycle plays an important role in the partitioning of carbon dioxide between the atmosphere and the ocean. The primary controls are the circulation of the ocean (a function of the climate system), and two important biogeochemical processes: the solubility pump and the biological pump, both of which act to create a global mean increase of dissolved inorganic carbon with depth.

The physical circulation and the interplay of the circulation and the biogeochemical processes are central to understanding the ocean carbon system and future concentrations of carbon dioxide in the atmosphere. In the ocean, the prevailing focus on surface conditions and heat transport has led to a comparative neglect of transport processes below about 800 m depth. For carbon cycle modelling, however, vertical transports and deep horizontal transports assume fundamental importance. The importance of the thermohaline circulation is obviously important (and insufficiently well understood; see above) in moving carbon from the surface to deeper layers. Similarly, the regional distribution of upwelling, which brings carbon- and nutrient-rich water to surface layers, is poorly known and inconsistently simulated in models. The lack of knowledge about the ventilation of the Southern Ocean provides an extreme, though not unique, example.

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Any complete model of the natural ocean carbon cycle should include the biological system; however, in many assessments of the oceanic uptake of anthropogenic CO it has been assumed that the biological system would not be affected by climate change, and therefore only the chemical solubility in addition to the physical circulation has been treated in models. This was based on the understanding that nitrate or other nutrients limit marine phytoplankton growth. There would therefore be no CO fertilization effect as has been suggested for terrestrial plants and that, unless there was a large change in the nutrient supply to the upper ocean because of a climate-induced shift in circulation, then no extra anthropogenic CO could be sequestered to the deep ocean by the organic matter pump. More recently, a number of studies have suggested possible ways in which the oceanic biological activity might be affected by climate change over a 200-year time-scale. Our understanding of the issues needs to be improved.

In sum, we do not understand sufficiently well the circulation of the world ocean. We do not adequately address biology in ocean carbon cycle models. As a result, present models may be unduly constrained in the range of responses they can show to changes in climate and ocean dynamics. A better understanding is required concerning the workings of nutrient constraints on productivity and the controls on the geographic distribution of biogeochemically important species and functional types in the ocean. To develop this understanding it will be necessary to combine remotely sensed information with a greatly expanded network of continuos biogeochemical monitoring sites, and to gather data on the space-time patterns of variability in species composition of marine ecosystems in relation to climate variability phenomena such as ENSO and NAO.

II.3.2 The terrestrial system

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The metabolic processes that are responsible for plant growth and maintenance and the microbial turnover, which is associated with dead organic matter decomposition, control the cycle carbon, nutrients, and water through plants and soil on both rapid and intermediate time scales. Moreover, these cycles affect the energy balance and provide key controls over biogenic trace gas production. Looking at the carbon fixation-organic material decomposition as a linked process, one sees that some of the carbon fixed by photosynthesis and incorporated into plant tissue is perhaps delayed from returning to the atmosphere until it is oxidised by decomposition or fire. This slower carbon loop through the terrestrial component of the carbon cycle affects the rate of growth of atmospheric CO concentration and, in its shorter term expression, imposes a seasonal cycle on that trend. The structure of terrestrial ecosystems, which respond on even longer time scales, is determined by the integrated response to changes in climate and to the intermediate time scale carbon-nutrient machinery. The loop is closed back to the climate system, since it is the structure of ecosystems, including species composition, that largely sets the terrestrial boundary condition of the climate in terms of surface roughness, albedo, and latent heat exchange.

Modelling interactions between terrestrial and atmospheric systems requires coupling successional models to biogeochemical models and physiological models that describe the exchange of water and energy between vegetation and the atmosphere at fine time scales. At each step toward longer time scales, the climate system integrates the more fine-scaled processes and applies feedbacks onto the terrestrial biome. At the finest time scales, the influence of temperature, radiation, humidity and winds has a dramatic effect on the ability of plants to transpire. On longer time scales, integrated weather patterns regulate biological processes such as the timing of leaf emergence or excision and rates of organic soil decay and turnover of inorganic nitrogen. The effect of climate at the annual or interannual scale defines the net gain or loss of carbon by the biota, its water status for the subsequent growing season, and even its ability to survive. As the temporal scale is extended, models must not only treat successional dynamics, but also ecosystem redistribution.

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This coupling across time scales represents a significant challenge. Immediate challenges that confront models of the terrestrial-atmosphere system include exchanges of carbon and water between the atmosphere and land, and the terrestrial sources and sinks of trace gases.

Achieving the ability to handle longer time scales is of fundamental importance. Prognostic models of terrestrial carbon cycle and terrestrial ecosystem processes are central for any consideration of the effects of environmental change and analysis of mitigation strategies; moreover, these demands will become even more significant as countries begin to adopt carbon emission targets.

Despite recent progress in developing and evaluating terrestrial biosphere models, several crucial questions remain open. For example, current models are highly inconsistent in the way they treat the response of primary production to climate variability and climate change—even though this response is fundamental to predictions of the total terrestrial carbon balance in a changing climate. Models also differ significantly in the degree of CO fertilisation they allow, and the extent to which CO responses are constrained by nutrient availability; the extent to which CO concentrations affect the global distribution of C and C photosynthetic pathways; and the impacts of climate, CO and land management on the tree-grass balance. These are all areas where modelling capability is limited by lack of knowledge, thus making it crucially important to expand observational and experimental research. Important areas are interannual variability in terrestrial fluxes and the interplay of warming, management, and CO enrichment responses at the ecosystem scale. Moreover, these issues must be far better resolved if there is to be an adequate verification scheme to confirm national performance in meeting targets for CO emissions.

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Finally, while progress will be made on modelling terrestrial processes, more integrative studies are also needed wherein terrestrial systems are coupled to models of the physical atmosphere and eventually to the chemical atmosphere as well.

II.5 Precipitation, soil moisture, and river flow: Elements of the hydrological cycle

Changes in precipitation could have significant impacts on society. Precipitation is an essential element in determining the availability of drinking water and the level of soil moisture. Improved treatment of precipitation is an essential step since patterns of predicted precipitation set the stage (and are partially determined by) evapotranspiration and the resulting distribution of soil moisture.

Soil moisture is a key component in the land surface schemes in climate models, since it is closely related to evapotranspiration and thus to the apportioning of sensible and latent heat fluxes. It is primary in the formation of runoff and hence river-flow. Further, soil moisture is an important determinant of ecosystem structure and therein a primary means by which climate regulates (and is partially regulated by) ecosystem distribution. Soil moisture is an important regulator of plant productivity and sustainability of natural ecosystems. In turn terrestrial ecosystems recycle water vapour at the land-surface/atmosphere boundary, exchange numerous important trace gases with the atmosphere, and transfer water and biogeochemical compounds to river systems. New efforts are needed in the development of models, which successfully represent the space-time dynamics interaction between soil, climate and vegetation. If water is a central controlling aspect, then the interaction necessarily passes all the way through the space-time dynamics of soil moisture. Finally, adequate soil moisture is an essential resource for human activity. Consequently, accurate prediction of soil moisture is crucial for simulation of the hydrological cycle, of soil and vegetation biochemistry, including the cycling of carbon and nutrients, and of ecosystem structure and distribution as well as climate.

River systems are linked to regional and continental-scale hydrology through interactions among precipitation, evapotranspiration, soil water, and runoff in terrestrial ecosystems. River systems, and more generally the entire global water cycle, control the movement of constituents over vast distances, from the continental land-masses to the world's oceans and to the atmosphere. Rivers are also central features of human settlement and development.

It appears, however, that a significant level of variance exists among land models, associated with unresolved differences among parameterisation details (particularly difficulties in the modelling of soil hydrology) and parameter sets. It is not known to what extent these differences in land-surface response translate into differences in global climate sensitivity although the uncertainty associated with the land-surface response while significant must be smaller than the uncertainty associated with clouds. There is model-based evidence indicating that these differences in the land-surface response may be significant for the simulation of the local land-surface climate and regional atmospheric climate changes.

Climate-induced changes in vegetation have potentially large climatic implications, but are still generally neglected in the coupled-model experiments used to estimate future changes in climate.

There is, obviously, a direct coupling between predicted soil moisture and predicted river flows and the availability of water for human use. Complex patterns of locally generated runoff are transformed into horizontal transport as rivers through the drainage basin. Moreover, any global perspective on surface hydrology must explicitly recognize the impact of human intervention in the water cycle, not only through climate and land-use change, but also through the operation of impoundments, interbasin transfers, and consumptive use. The spatial resolution of current global climate models, roughly two hundred kilometres, is too coarse to simulate the impact of global change on most individual river basins. This will, hopefully, change in the future.

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Data is also a central issue. Climate time series and monthly discharge data for the past several decades at selected locations provide the opportunity for important tests of models, including appraisal of the impact of episodic events, such as El Niño, on surface water balance and river discharge. It will be necessary to inventory, document, and make available such data sets to identify gaps in our knowledge, and where it is necessary to collect additional data. Even in the best-represented regions of the globe coherent time series are available for only the last 30 years or less. This lack of data constrains our ability to construct and test riverine flux models. Standardised protocols, in terms of sampling frequency, spatial distribution of sampling networks, and chemical analyses are needed to ensure the production of comparable data sets in disparate parts of the globe. Upgrades of the basic monitoring system for discharge and riverborne constituents at the large scale are therefore required.

In sum, hydrological processes and energy exchange, especially those involving clouds, surface exchanges, and interactions of these with radiation are crucial for further progress in modelling the atmosphere. Feedbacks with land require careful attention to the treatments of evapotranspiration, soil moisture storage, and runoff. All of these occur on spatial scales fine compared to the model meshes, so the question of scaling must be addressed. These improvements must be paralleled by the acquisition of global data sets for validation of these treatments. Validation of models against global and regional requirements for conservation of energy is especially important in this regard. As noted in Chapter 8 of the soon to be published Third Assessment Report of Working Group 1 of the IPCC, "Uncertainty in land processes, coupled with uncertainty in parameter data combines, at this time, to limit the confidence we have in the simulated regional impacts of increasing CO."

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II.6 Trace gases, aerosols, and the climate system

The goal is a completely interactive simulation of the dynamical, radiative, and chemical processes in the atmosphere-ocean-land system with a central theme of characterising adequately the radiative forcing in the past, in the present, and into the future (See, for instance, Third Assessment Report of Working Group 1 of the IPCC Chapter 6 and 9). Such a model will be essential in future studies of the broad question on the role of the oceans, terrestrial ecosystems, and human activities in the regulation of atmospheric concentrations of CO and other radiatively active atmospheric constituents. It will be required for understanding tropospheric trace constituents such as nitrogen oxides, ozone, and sulfate aerosols. Nitrogen oxides are believed to control the production and destruction of tropospheric ozone, which controls the chemical reactivity of the lower atmosphere and is itself a significant greenhouse gas. Tropospheric sulphate aerosols, carbonaceous aerosols from both natural and anthropogenic processes, dust, and sea salt, on the other hand, are believed to affect significantly the Earth's radiation budget by scattering solar radiation and their effects on clouds. Systematic observations of different terrestrial ecosystems and surface marine systems under variable meteorological conditions are needed along with the development of ecosystem and surface models that will provide parameterisations of these exchanges.

Models that incorporate atmospheric chemical processes provide the basis for much of our current understanding in such critical problem areas as acid rain, photochemical smog production in the troposphere, and depletion of the ozone layer in the stratosphere. These formidable problems require models that include chemical, dynamical, and radiative processes, which through their mutual interactions determine the circulation, thermal structure, and distribution of constituents in the atmosphere. That is, the problems require a coupling of the physics and chemistry of the atmosphere. Furthermore, the models must be applicable on a variety of spatial (regional-to-global) and temporal (days-to-decades) scales. A particularly important and challenging issue is the need to reduce the uncertainty on the size and spatial pattern of the indirect aerosol effects.

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We also need improved understanding of the processes involving clouds, surface exchanges, and their interactions with radiation. The coupling of aerosols with both the energy and water cycles as well as with the chemistry components of the system is of increasing importance. Determining feedbacks between the land surface and other elements of the climate system will require careful attention to the treatments of evapotranspiration, soil moisture storage, and runoff. All of these occur on spatial scales that are small compared to the model meshes, so the question of scaling must be addressed. These improvements must be paralleled by the acquisition of global data sets for validation of these treatments. Validation of models against global and regional requirements for conservation of energy is especially important in this regard.

Fine-scaled, three-dimensional models of chemically active trace gases in the troposphere are needed to resolve transport processes at the highest possible resolution. These models should be designed to simulate the chemistry and transport of atmospheric tracers on global and regional scales, with accurate parameterisations of sub-scale processes that affect the chemical composition of the troposphere. It is therefore necessary to pursue an ambitious long-term program to develop comprehensive models of the troposphere system, including chemical, dynamical, radiative, and eventually biological components.

The short-lived radiatively important species pose an observational challenge. The fact that they are short-lived implies that observations of the concentrations are needed over wide spatial regions and over long period of times. This is particularly important for aerosols. The current uncertainties are nontrivial and need to be reduced.

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In addition to this needed expansion in the attack on uncertainties in the climate system, there is an important new challenge that should now be addressed more aggressively. It is time to link more formally physical climate-biogeochemical models with models of the human system. At present, human influences generally are treated only through emission scenarios that provide external forcings to the climate system. In future comprehensive models, human activities will interact with the dynamics of physical, chemical, and biological subsystems through a diverse set of contributing activities, feedbacks, and responses. This does not mean that it is necessary or even logical to attempt to develop prognostic models of human actions since much will remain inherently unpredictable; however, the scenarios analysis could and should be more fully coupled to the coupled physical climate-biogeochemical system.

As part of the foundation building to meet this challenge, we turn attention now to the Human System.

III. THE HUMAN SYSTEM

III.1 Overview

Human processes are critically linked to the climate system as contributing causes of global change, as determinants of impacts, and through responses. Representing these linkages poses perhaps the greatest challenge to modelling the total Earth system. But understanding them is essential to understanding the behaviour of the whole system and to providing useful advice to inform policy and response.

Land-use change illustrates the potential complexity of linkages between human activity and major non-human components of the Earth system. The terrestrial biosphere is fundamentally modified by land clearing for agriculture, industrialisation, urbanisation, and by forest and rangeland management practices. These changes affect the atmosphere through an altered energy balance over the more intensively managed parts of the land surface, as well as through changed fluxes of water, carbon dioxide, methane and other trace gases between soils, vegetation, and the atmosphere. Changed land use also greatly alters the fluxes of carbon, nutrients, and inorganic sediments into river systems, and consequently into oceanic coastal zones.

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The response of the total Earth system to these changes in anthropogenic forcing is currently not known. Sensitivity studies with altered land cover distributions in general circulation models have shown that drastic changes, such as total deforestation of all tropical or boreal forests, may lead to feedbacks in atmospheric circulation and a changed climate that would not support the original vegetation (e.g., Claussen, 1996). Regional climate simulations, on the other hand, have shown that at the continental scale, important teleconnections may exist through which more modest tropical forest clearing may cause a change in climate in undisturbed areas. Coupling the global to the local is a key challenge; regional studies may prove to be uniquely valuable.

Human land use change will continue and probably accelerate due to increasing demands for food and fibre, changes in forest and water management practices, and possibly large-scale projects to sequester carbon in forests or to produce biomass fuels. In addition, anthropogenic changes in material and energy fluxes, resulting from such activities as fossil-fuel combustion and chemical fertiliser use, are expected to increase in the coming decades. Predictions of changes in the carbon and nitrogen cycles are sensitive to estimates of human activity and predictions of the impacts of these global changes must take into account human vulnerability, adaptation, and response. Predicting the future response of the Earth system to changes in climate and in parallel to changes in land use and land cover will require projections of trends in the human contributions to these global changes; this sort of modelling presents difficult challenges because of the multiple factors operating at local, regional, continental, and global levels to influence local land-use decisions.

In sum, the human element probably represents the most important aspect both of the causes and effects of climate change and environmental impacts. And any policy intervention will have human activities as its immediate target.

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III.2 Humans: Drivers of global change; recipients of global change

The provision of useful guidance to inform policy requires observation and description of human contributions to global change, as well as theoretical studies of the underlying social processes that shape them. We also need to understand how global change affects human welfare. This requires not merely studies of direct exposure but also of the capacity to respond.

Causal models of social processes have large uncertainties, and pose problems that are of a qualitatively different character than those encountered in modeling non-human components of the Earth system. This is due, first and foremost, to the inherent reflexivity of human behavior; i.e., the fact that human beings have intellectual capabilities and emotional endowments enabling them to invent new solutions and transcend established ways that no other species can do. As a consequence, predictive models, as is well known, may well alter the behavior that they seek to predict and explain—indeed, such models are sometimes deliberately used exactly for that purpose. Moreover, the diversity of societies, cultures, and political and economic systems often frustrates attempts to generalize findings and propositions from one setting to another. Representation of human behavior at the micro (individual) and macro (collective) scale may require fundamentally different approaches.

These kinds of difficulties intrinsically limit the predictive power that can be ascribed to models of social processes. As a consequence, research on human drivers and responses to climate change cannot be expected to produce conventional predictions beyond a very short time horizon. This does not imply, however, that research on human behavior and social processes cannot provide knowledge and insight that can inform policy deliberations. A considerable amount of basic knowledge and insight exist, and this knowledge can be used, inter alia, for constructing scenarios showing plausible trajectories and identifying the critical factors that will have to be targeted in order to switch from one trajectory to another. From the perspective of policy-makers, this can indeed be an important contribution.

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To make the most out of this potential, further progress is required along two main frontiers. One challenge is to develop a more integrated understanding of social systems and human behavior. With some exceptions, the first generation of models in this area represented 'the human system' by a few key variables. For example, resource use was often conceived of as a function of population size and income level. The performance of such simplistic models was by and large poor. It is abundantly clear that the impact of human activities as drivers of climate change depends upon a complex set of interrelated factors, including also technologies in use, social institutions, and individual beliefs, attitudes, and values. At present, it seems fair to say that we have a reasonably good theoretical grasp on important types of institutions, such as markets and hierarchies, in ideal-type form. What we need to understand better is how their impure real-world counterparts work, and to improve our understanding of the intricate interplay of institutional complexes, i.e., how markets, governments and other social institutions interact to shape human behavior. Research in political economy clearly indicates that phenomena such as economic growth are to a significant extent affected by the functioning of interlocking networks of institutional arrangements.

The other main challenge is to find better ways of integrating models of the biogeophysical Earth system with models of social systems and human behavior. Some encouraging progress has been made at this interface, particularly over the last decade. For example, there has been a rapid increase in attempts to integrate representations of human activities in models with explicit formal linkages to other components of the Earth system. Such integrated assessment models have offered preliminary characterizations of human-climate linkages, particularly through models of multiple linked human and climate stresses on land cover. Moreover, they have provided preliminary characterization of broad classes of policy responses, and have been employed to characterize and prioritize policy-relevant uncertainties.

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Yet, effective integration is frustrated by at least two main obstacles. One is incongruity of temporal and spatial scales. Social science research cannot match the long time horizons of much natural science research. On the other hand, in studying consequences for human welfare and responses to these consequences social scientists need estimates of biophysical impacts of climate change differentiated by political units or even smaller social systems. Aggregate global-scale estimates are of limited use in this context; human sensitivity to climate change varies significantly across regions and social groups, and so does response capacity. We can expect to see some progress in alleviating the spatial resolution problem, as regional-scale models of climate change are further developed, but we have to recognize that the scale problems are fundamental and that no quick fixes are in sight. The other problem pertains to the interface between different methodological approaches. In particular, concerted efforts are required to develop better tools for coupling approaches relying on numerical modeling with "softer" approaches using interpretative frameworks and qualitative methods. Some of these differences are too profound to be eliminated, but that does not imply that bridges cannot be built. Learning how to work more effectively across these methodological divides is essential to the further development of integrated global change research. Again, some encouraging progress is being made.

IV. OUTLOOK

There is a growing recognition in the scientific community and more broadly that:

The Earth functions as a system, with properties and behaviour that are characteristic of the system as a whole. These include critical thresholds, 'switch' or 'control' points, strong nonlinearities, teleconnections, chaotic elements, and unresolvable uncertainties. Understanding components of the Earth system is critically important, but is insufficient on its own to understand the functioning of the Earth system as a whole.

Humans are now a significant force in the Earth system, altering key process rates and absorbing the impacts of global environmental changes.

A scientific understanding of the Earth system is required to help human societies develop in ways that sustain the global life support system. The clear challenge of understanding climate variability and change and the associated consequences and feedbacks is a specific and important example of the need for a scientific understanding of the Earth as a system. It is also clear that the scientific study of the whole Earth system, taking account of its full functional and geographical complexity over time, requires an unprecedented effort of international collaboration. It is well beyond the scope of individual countries and regions.

The world's scientific community, working in part through the three global environmental change programmes (the International Geosphere-Biosphere Programme, the International Human Dimensions Programme on Global Environmental Change, and the World Climate Research Programme, have built a solid base for understanding the Earth system. They also have developed effective and efficient strategies for implementing global environmental change research at the international level. The challenge to IGBP, IHDP and WCRP is to build an international programme of Earth system science, driven by a common mission and common questions, employing visionary and creative scientific approaches, and based on an ever closer collaboration across disciplines, research themes, programmes, nations and regions.

We need to build on our existing understanding of the Earth System and its interactive human and non-human processes through time in order to:

improve evaluation and understanding of current and future global change; and

place on an increasingly firm scientific basis the challenge of sustaining the global environment for future human societies.

The climate system is particularly challenging since it is known that components in the system are inherently chaotic and there are central components, which affect the system in a nonlinear manner and potentially could switch the sign of critical feedbacks. The nonlinear processes include the basic dynamical response of the climate system and the interactions between the different components. These complex, nonlinear dynamics are an inherent aspect of the climate system. Amongst the important nonlinear processes are the role of clouds, the thermohaline circulation, and sea ice. There are other broad nonlinear components, the biogeochemical system and, in particular, the carbon system, the hydrological cycle, and the chemistry of the atmosphere.

Give the complexity of the climate system and the inherent multi-decadal timescale, there is a central and unavoidable need for long-term consistent data to support climate and environmental change investigations. Data from the present and recent past, credible global climate-relevant data for the last few centuries, along with lower frequency data for the last several millennia are all needed. Research observational data sets that span significant temporal and spatial scales are needed. Such data must be adequate in temporal and spatial coverage, in parameters measured, and in precision to permit meaningful validation. We are still unfortunately short of data for the quantitative assessment of extremes on the global scale in the observed climate.

In sum, there is a need for

More comprehensive data, contemporary, historical, and paleological, relevant to the climate system;

Expanded process studies that more clearly elucidate the structure of fundamental components of the Earth system and the potential for changes in these central components;

Greater effort in testing and developing increasingly comprehensive and sophisticated Earth system models;

Increased emphasis upon producing ensemble calculations of Earth system models that yield descriptions of the likelihood of a broad range of different possibilities, and finally,

New efforts in understanding the fundamental behaviour of large-scale nonlinear systems.

These are significant challenges, but they are not insurmountable. The challenges to understanding the Earth system including the human component are daunting, and the pressing needs are significant. However, the opportunity for progress exists, and, in fact, this opportunity simply must be realised. The issues are too important, and they will not vanish. The challenges simply must be met.

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TESTIMONY SUMMARY OF BERRIEN MOORE III

SUMMARY

Many factors continue to limit our ability to detect, attribute, and understand current climate change and to project what future climate changes may be. Further effort is needed in ten broad areas:

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Arrest the decline of observational networks in many parts of the world. Unless networks are significantly improved, it may be difficult or impossible to detect climate change over large parts of the globe.

Sustain and expand the observational foundation for climate studies by providing accurate, long-term consistent data, including implementation of a strategy for integrated global observations. Given the complexity of the climate system and the inherent multi-decadal timescale, there is a need for long-term consistent data to support climate and environmental change investigations and projections. Data from the present and recent past, climate-relevant data for the last few centuries and for the last several millennia, are all needed. There is a particular shortage of data in polar regions and data for the quantitative assessment of extremes on the global scale.

Understand better the mechanisms and factors leading to changes in radiative forcing; in particular, improve the observations of the spatial distribution of greenhouse gases and aerosols. It is particularly important that improvements are realized in deriving concentrations from emissions of gases—particularly aerosols, and in addressing biogeochemical sequestration and cycling; specifically, in determining the spatial-temporal distribution of carbon dioxide sources and sinks, currently and in the future. Observations are needed that would decisively improve our ability to model the carbon cycle; in addition, a dense and well-calibrated network of stations for monitoring CO and O concentrations will also be required for international verification of carbon sinks. Improvements in deriving concentrations from emissions of gases and in the prediction and assessment of direct and indirect aerosol forcing will require an integrated effort involving in situ observations, satellite remote sensing, field campaigns and modeling.

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Understand and characterize the important unresolved processes and feedbacks, both physical and biogeochemical, in the climate system. Increased understanding is needed to improve prognostic capabilities generally. The interplay of observation and models will be the key for progress. The rapid forcing of a nonlinear system has a high prospect of producing surprises.

Address more completely patterns of long-term climate variability. This topic arises both in model calculations and in the climate system. In simulations, the issue of climate drift within model calculations needs to be clarified better, in part because in compounds there is the difficulty of distinguishing signal and noise. With respect to the long-term natural variability in the climate system *per se,* it is important to understand this variability and to expand the emerging capability of predicting patterns of organized variability such as ENSO. This predictive capability is both a valuable test of model performance and a useful contribution in natural resource and economic management.

Explore more fully the probabilistic character of future climate states by developing multiple ensembles of model calculations. The climate system is a coupled nonlinear chaotic system, and therefore the long-term prediction of future climate states is not possible. Rather the focus must be upon the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. Addressing adequately the statistical nature of climate is computationally intensive and requires the application of new methods of model diagnosis, but such statistical information is essential.

Expand significantly the computing resources available to address the issues of global climate and environmental change. The dual requirements of using large, complex models to perform multiple transient calculations place extraordinary demands for additional computing resources. These demands are significant and they are not being met. This is limiting progress in the United States.

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Improve the integrated hierarchy of global and regional climate models with emphasis on improving the simulation of regional impacts and extreme weather events. There is the potential for increased understanding of extreme events by employing regional climate models; however, there are also challenges to realizing this potential. It will require improvements in the understanding of the coupling between the major atmospheric, oceanic, and terrestrial systems, and extensive diagnostic modeling and observational studies that evaluate and improve simulative performance. A particularly important issue is the adequacy of data needed to attack the question of changes in extreme events.

Link more formally physical climate-biogeochemical models with models of the human system and thereby provide the basis for expanded exploration of possible cause-effect-cause patterns linking human and non-human components of the Earth system. At present, human influences generally are treated only through emission scenarios that provide external forcings to the climate system. In the future more comprehensive models of human activities need to interact with the dynamics of physical, chemical, and biological subsystems through a diverse set of contributing activities, feedbacks, and responses.

Accelerate international progress in understanding climate change by strengthening the international framework that is needed to co-ordinate national and institutional efforts so that research, computational, and observational resources may be used to the greatest overall advantage. Elements of this framework exist in the international programs supported by the International Council for Science (ICSU), the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the United Nations Educational Scientific and Cultural Organization (UNESCO). There is a corresponding need for strengthening the cooperation within the international research community, for building research capacity in many regions, and, as is the goal of this assessment, for effectively describing research advances in terms that are relevant to decision-making.

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The challenges to understanding the Earth system, including the human component, are daunting, but these challenges simply must be met.

BIOGRAPHY FOR BERRIEN MOORE III

Berrien Moore III joined the University of New Hampshire (UNH) faculty in 1969, soon after receiving his Ph.D. in mathematics from the University of Virginia. A Professor of Systems Research, he received the University's 1993 Excellence in Research Award and was named University Distinguished Professor in 1997; there are only two such positions at UNH. He has led the Institute for the Study of Earth, Oceans and Space at UNH as Director since 1987.

He has been a visiting scientist at the International Institute of Meteorology at the University of Stockholm, the Woods Hole Oceanographic Institution, the East-West Center in Hawaii, and a visiting senior scientist at the Laboratorie de Physique et Chemie Marines at the Universite de Paris.

Professor Moore has authored over 100 papers on the carbon cycle, global biogeochemical cycles, Global Change as well as numerous policy documents in the area of the global environment.

Professor Moore has served as a committee member of the NASA Space and Earth Science Advisory Committee, which published its report in 1986: "The Crisis in Space and Earth Science: A Time for a New Commitment." Other committees and panels on which Professor Moore has served include the NASA Advisory Council's Committee on Earth System Science, the National Academy of Sciences' Board on Global Change, the Space Science Board's Committee on Earth Science, and the Science Executive Committee for the Earth Observing System (EOS).

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Professor Moore was appointed chairman in 1987 of NASA's senior science advisory panel, the Space Science and Applications Advisory Committee, and as such, was a member of the NASA Advisory Council. In May 1992, upon completion of his Chairmanship, Professor Moore was presented with NASA's highest civilian award, the NASA Distinguished Public Service Medal for outstanding service to the agency.

Professor Moore has contributed actively to committees at the National Academy of Science; most recently, he served as Chairman of the Academy's Committee on International Space Programs of the Space Studies Board. This committee, in collaboration with the European Space Sciences Committee, jointly published *''US-European Collaboration in Space Science.''* In 1999, he completed his Chairmanship of the National Academy's Committee on Global Change Research with the publication of *''Global Environmental Change: Research Pathways for the Next Decade.''*

In January of 1998 Professor Moore assumed the Chair of the overarching Scientific Committee (SC) of the International Geosphere-Biosphere Programme (IGBP). Prior to assuming Chair, he led the IGBP Task Force on Global Analysis, Interpretation, and Modelling (GAIM) for five years. As Chair of the SC-IGBP, he serves as lead author within the Intergovernmental Panel on Climate Change (IPCC).

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POST-HEARING QUESTIONS

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Replies from Dr. Berrien Moore III

Attachment I

Observations.

With regards to what can be done to stabilize the observing capabilities, I can only say that there is no short-cut here and that one simply must recognize this necessity. I think that it must be implemented by an operational agency—I would recommend NOAA. But NOAA often has budget problems and it has many demands on its resources; therefore, Congress must simply recognize this important requirement and provide NOAA the resources.

There are several additional measurements that are needed. I will focus on CO, and I shall treat this in some depth since it is so important.

Today abundances of CO and CH in the atmosphere are at the highest they have been in the past 25 million years. The current concentration in CO in the atmosphere (370 ppmv) has increased by 30% since the pre-industrial era 200 years ago and has doubled its value (180 ppmv) during the glacial epochs. Current levels of CH are nearly triple the pre-industrial value (700 ppmv) and 6-fold the glacial values. The current high level of these trace constituents in the atmosphere is already a significant change in a fundamental forcing on the Earth's climate system.

The contemporary increase in these radiatively-important trace gases is intimately tied to human use of energy and exploitation of natural resources to advance its welfare. The recent (since 1800**A.D.**) increase in CO is caused primarily by the combustion of fossil fuels and secondarily by landcover change. That the increase is due primarily to the addition of fossil carbon by industrialization is confirmed by the decrease in the ratio of 1BC:1B   C and 1BC:1B   C in CO, as well as by the increasing north-south gradient of atmospheric CO.

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Only 50–60% of the CO from fossil fuel combustion has remained in the atmosphere. Analysis using the decreasing 1BC/1B   C and O/N ratios in the atmosphere, modeling has shown that the land and oceans have sequestered the non-airborne fraction, in approximately equal proportions; however, the proportional balance varies in time (and space). The current state of the science cannot completely account for the growth rate and inter-annual variations of atmospheric CO with confidence.

The geographic distribution of the land and ocean sinks has likewise remained elusive. Because of the difficulty of direct oceanic and terrestrial measurements compounded by the problem in extrapolating such measurements in space and time, estimates of the locations of the land and ocean sinks have begun to rely additionally on the sparse atmospheric CO measurements. Most of these measurements are located in marine remote locations, and the inversion for even *continental* sources/sinks using atmospheric circulation/transport models remains an under-determined problem.

This indeterminacy is important.

As nations seek to develop strategies to manage their carbon emissions and sequestration, the capability to quantify the present-day *regional* carbon sources/sinks and to understand the underlying mechanisms are pre-requisites to prediction and informed policy decisions. Knowledge of today's regional CO sources and sinks, including their mechanisms and their sensitivity to climate perturbations, is central to theoretical predictions of future levels. Independent information on spatial and temporal patterns of CO sources and sinks is of extraordinary value for challenging processed-based terrestrial and oceanic carbon cycle models. It is obvious that this information is also highly relevant for meeting current and future needs of the policy community.

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Adequate knowledge of the source-sink pattern is not at hand; for some regions like the vast expanse of Eurasia, we do not know even if the region is acting as a net carbon source or a net carbon sink from year-to-year. *This gap in our understanding is in large measure due to an inadequate system to measure the patterns (particularly gradients) in atmospheric CO*.

The current system for measuring atmospheric CO is characterized as providing a relatively small number (<100 globally) of remarkably accurate and precise measurements. The observing sites are located mainly in remote marine locations where the biweekly measurements may be representative of the CO concentration over extended spatial-temporal scales. It is only until recently that monitoring over continental regions began using very tall towers. How these site-specific observations can be extrapolated regionally remains an intense area of research. *It is important that in-situ atmospheric measurements be maintained and expected where new sites are possible.*

In sum, our current knowledge of regional carbon sources and sinks is based on sparse samples on land, at sea and in the atmosphere. The atmosphere is a fast but incomplete mixer and integrator of spatially and temporally varying surface fluxes and so the distribution and temporal evolution of CO in the atmosphere can be used to quantify surface fluxes. The wide range of inferred regional carbon fluxes is a consequence of the fact the atmosphere is severely under-sampled. Simply stated, the current set of observations is simply too sparse, and this sparseness leaves the source-sink determination via inverse methods significantly under-determined. Furthermore, when we have process understanding or carbon inventories from local studies, or satellite observations (e.g., MODIS) of a subset of the carbon exchange processes, it is difficult to "connect" this understanding to global CO patterns because the atmosphere is so under-sampled. Expansion of in-situ ocean and terrestrial carbon measuremnts is clearly important as is the improvement in our process level understanding, but without comprehensive spatial coverage of the atmospheric measurements of carbon dioxide, uncertainty cannot even be localized to transport model error, data error, or inversion procedures.

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Global measurements of atmospheric CO would shift the problem from an under-determined or indeterminate system to an over-determined system. This shift is fundamental; it allows the localization of CO fluxes in time and space. Satellite measurements of the distribution of global atmospheric CO would fill this gap in scale. Measurements that densely sample the atmosphere would provide a crucial constraint, allowing uncertainty in transport versus other information (on source and sink characteristics such as from surface imagery and models), to be separated and reduced. *Satellite observations of atmospheric CO* are the needed complement to the current observational system of highly accurate, sparsely distributed measurements of atmospheric CO. This complement is the key to answering important questions regarding spatial and temporal variability of carbon sources and sinks. These space-based measurements must be without temporal (seasonal or diurnal) or spatial bias.

Computing Resources.

Regarding the computing power (or lack thereof). It is relatively simple—treat the purchase of computers like cars—it should not matter where they are made. We need high-end machines. The U.S. scientific community has not been allowed resources to purchase high-end machines and when resources are provided, they have come with restrictions to buy domestic machines. This is shortsighted and has resulted in the U.S. falling behind other countries and regions in certain aspects of climate modeling.

There is also a strategy issue and I would like to refer the Congress to Chapter 14 on the Third Assessment report of the IPCC. I quote from that Chapter for which I served as the Coordinating Lead Author.

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"There is a natural tendency to produce models at finer spatial scales that include both a wider array of processes and more refined descriptions. Higher resolution can lead to better simulations of atmospheric dynamics and hydrology (Section 8.9.1), less diffusive oceanic simulations, and improved representation of topography. In the atmosphere, fine scale topography is particularly important for resolving small-scale precipitation patterns (Section 8.9.1). In the ocean, bottom topography is very important for the various boundary flows (Section 7.3.4.1). The use of higher oceanic resolution also improves the simulation of internal variability such as ENSO (Section 8.7.1). However, in spite of the use of higher resolution, important climatic processes still are not resolved by the model's grid necessitating the continued use of sub-grid scale parameterizations.

It is anticipated that the grids used in the ocean sub-components of the coupled climate models will begin to resolve eddies by the next Report. As the oceanic eddies become resolved by the grid, the need for large diffusion coefficients and various mixing schemes should be reduced (Section 8.9.3; see also, however, the discussion in Section 8.9.2)). In addition, the amount of diapycnal mixing, which is used for numerical stability in this class of ocean models, will also be reduced as the grid spacing becomes smaller. This reduction in the sub-grid scale oceanic mixing should reduce the uncertainty associated with the mixing schemes and coefficients currently being used.

Underlying this issue of scale and detail is an important tension. As the spatial and process detail in a model is increased, the required computing resources increase, often significantly; models with less detail may miss important nonlinear dynamics and feedbacks that effect model results significantly, and yet simpler models may be more appropriate to generating the needed statistics. The issue of spatial detail is intertwined with the representation of the physical (and other) processes, and hence the need for a balance between level of process detail and spatial detail. These tensions must be recognized forthrightly, and *strategies must be devised to use the available computing resources wisely.* Analyses to determine the benefits of finer scale and increased resolution need to be careful considered. These considerations must also recognize that the potential predictive capability will be unavoidably statistical, and hence it must be produced with statistically relevant information. This implies that a variety of integrations (and models) must be used to produce an ensemble of climate states. Climate states are defined in terms of averages and statistical quantities applying over a period typically of decades. See Sections 7.1.3 and 9.2.2.

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Fortunately, many groups have performed ensemble integrations, that is, multiple integrations with a single model using identical radiative forcing scenarios but different initial conditions. Ensemble integrations yield estimates of the variability of the response for a given model. They are also useful in determining to what extent the initial conditions affect the magnitude and pattern of the response. Furthermore, many groups now have performed model integrations using similar radiative forcings. This allows ensembles of model results to be constructed (See Section 9.3; see also the end of Section 7.1.3 for an interesting question about ensemble formation).

In sum, a strategy must recognize what is possible. In climate research and modelling, we should recognize that we are dealing with a coupled nonlinear chaotic system, and therefore that the long-term prediction of future climate states is not possible. The most we can expect to achieve is the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. This reduces climate change to the discernment of significant differences in the statistics of such ensembles. The generation of such model ensembles will require the dedication of greatly increased computer resources and the application of new methods of model diagnosis. Addressing adequately the statistical nature of climate is computationally intensive, *but such statistical information as essential."*

Data Points on Ocean vs. Land.

Let me only state that we are data starved on land and in the ocean and in the atmosphere.

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Integrated ocean-observing system.

This was treated adequately by the other speakers.

Kyoto.

It appears that many issues are at work here. I believe a key issue, as stated in my lengthy answer to the first question, is the issue of sources and sinks. The key new measurement is the space-based measurement of atmospheric CO (total column densities would be sufficient for the next decade).

USGCRP

This is too complex for a short answer—we tried to treat this in the NRC "Pathways" Report. I think that it is well treated there. *It is important; I do not believe that assigning a "lead agency" would work.*

Human Resources.

I believe that generally the level of human resources is a strength of the U.S. effort; however, it is not without weaknesses. The principal weakness that I see is a systemic problem: Too few American students are going into science; this is particularly true of the space and Earth (broadly defined) sciences. I believe that this is true for several reasons, but two causes are a lack of graduate fellowships at an adequate stipend and a perceived lack of opportunity in the field: too little money for too many proposals and hence not a sufficiently positive probability of success and hence not a "wise" career choice. Unfortunately, there is some truth to this perception.

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Attachment III

Human Dimensions
(FROM IPCC TAR, WORKING GROUP 1; CHAPTER 14)

The provision of useful guidance to inform policy requires observation and description of human contributions to global change, as well as theoretical studies of the underlying social processes that shape them. We also need to understand how global change affects human welfare. This requires not merely studies of direct exposure but also of the capacity to respond.

Causal models of social processes have large uncertainties, and pose problems that are of a qualitatively different character than those encountered in modeling non-human components of the Earth system. This is due, first and foremost, to the inherent *reflexivity* of human behavior; i.e., the fact that human beings have intellectual capabilities and emotional endowments enabling them to invent new solutions and transcend established "laws" in ways that no other species can do. As a consequence, predictive models may well alter the behavior that they seek to predict and explain—indeed, such models are sometimes deliberately used exactly for that purpose. Moreover, the diversity of societies, cultures, and political and economic systems often frustrates attempts to generalize findings and propositions from one setting to another. Representation of human behavior at the micro (individual) and macro (collective) scale may require fundamentally different approaches.

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These kinds of difficulties intrinsically limit the predictive power that can be ascribed to models of social processes. As a consequence, research on human drivers and responses to climate change cannot be expected to produce conventional predictions beyond a very short time horizon. This does not imply, however, that research on human behavior and social processes cannot provide knowledge and insight that can inform policy deliberations. A considerable amount of basic knowledge and insight exist, and this knowledge can be used, *inter alia,* for constructing *scenarios* showing plausible trajectories and identifying the critical factors that will have to be targeted in order to switch from one trajectory to another. From the perspective of policy-makers, this can indeed be an important contribution.

To make the most out of this potential, further progress is required along two main frontiers. One challenge is to develop a more integrated understanding of social systems and human behavior. With some exceptions, the first generation of models in this area represented 'the human system' by a few key variables. For example, resource use was often conceived of as a function of population size and income level. The performance of such simplistic models was by and large poor. It is abundantly clear that the impact of human activities as drivers of climate change depends upon a complex set of interrelated factors, including also technologies in use, social institutions, and individual beliefs, attitudes, and values. At present, it seems fair to say that we have a reasonably good theoretical grasp on important types of institutions, such as markets and hierarchies, in ideal-type form. What we need to understand better is how their impure real-world counterparts work, and to improve our understanding of the intricate interplay of institutional *complexes,* i.e., how markets, governments and other social institutions interact to shape human behavior. Research in political economy clearly indicates that phenomena such as economic growth are to a significant extent affected by the functioning of interlocking *networks* of institutional arrangements.

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Similarly, we have a fairly good grasp on particular kinds of intellectual processes—in particular, the logic of rational choice—but we are doing less well when it comes to understanding how beliefs, attitudes and values change and how change in these factors in turn affects manifest human behavior, such as consumption patterns. To address these challenges we need more interdisciplinary research designed to integrate knowledge from different fields and subfields into a more holistic understanding of 'the human system'. The intellectual and organizational problems involved should not be underestimated, but we are confident that the prospects for making progress along this frontier are better now than ever before.

The other main challenge is to find better ways of integrating models of the biogeophysical Earth system with models of social systems and human behavior. Some encouraging progress has been made at this interface, particularly over the last decade. For example, there has been a rapid increase in attempts to integrate representations of human activities in models with explicit formal linkages to other components of the Earth system. Such integrated assessment models have offered preliminary characterizations of human-climate linkages, particularly through models of multiple linked human and climate stresses on land cover. Moreover, they have provided preliminary characterization of broad classes of policy responses, and have been employed to characterize and prioritize policy-relevant uncertainties.

Yet, effective integration is frustrated by at least two main obstacles. One is incongruity of temporal and spatial scales. Social science research cannot match the long time horizons of much natural science research. On the other hand, in studying consequences for human welfare and responses to these consequences social scientists need estimates of biophysical impacts of climate change differentiated by political units or even smaller social systems. Aggregate global-scale estimates are of limited use in this context; human sensitivity to climate change varies significantly across regions and social groups, and so does response capacity. We can expect to see some progress in alleviating the spatial resolution problem, as regional-scale models of climate change are further developed, but we have to recognize that the scale problems are fundamental and that no quick fixes are in sight. The other problem pertains to the interface between different methodological approaches. In particular, concerted efforts are required to develop better tools for coupling approaches relying on numerical modeling with "softer" approaches using interpretative frameworks and qualitative methods. Some of these differences are too profound to be eliminated, but that does not imply that bridges cannot be built. Learning how to work more effectively across these methodological divides is essential to the further development of integrated global change research. Again, some encouraging progress is being made.

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Attachment IV

Role of Clouds
(FROM IPCC TAR, WORKING GROUP 1; CHAPTER 14)

The role of clouds in the climate system continues to challenge the modelling of climate (e.g., TAR, Section 7.2.2). It is generally accepted that the net effect of clouds on the radiative balance of the planet is negative and has an average magnitude of about 10–20 Wm– . This balance consists of a short-wave cooling (the albedo effect) of about 40–50 Wm– and a long-wave warming of about 30 Wm– . Unfortunately, the size of the uncertainties in this budget is large when compared to the expected anthropogenic greenhouse forcing. Although we know that the overall net effect of clouds on the radiative balance is slightly negative, we do not know the sign of cloud feedback with respect to the increase of greenhouse gases, and it may vary with the region. In fact, the basic issue of the nature of the future cloud feedback is not clear. Will it remain negative? If the planet warms, then it is plausible that evaporation will increase which probably implies that liquid water content will increase but the volume of clouds may not. What will be the effect and how will the effects be distributed in time and space. Finally, the issue of cloud feedbacks is also coupled to the very difficult issue of indirect aerosol forcing (TAR, Section 5.3).

The importance of clouds was summarized by the 1996 Working Group 1 report of the IPCC: "The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle" (Kattenberg *et al.*, 1996, p345). And yet, the single greatest source of uncertainty in the estimates of the climate sensitivity continues tote clouds (see TAR, Section also 7.2). Since the SAR, there have been a number of improvements in the simulation of both the cloud distribution and in the radiative properties of clouds (TAR, Section 7.2.2). The simulation of cloud distribution has improved as the overall simulation of the atmospheric models has improved. In addition, the cloud sub-component models used in the coupled modes have become more realistic Also, our understanding of the radiative properties of clouds and their effects on climate sensitivity have improved. And yet in Section 7.2.2 we find that, "In spite of these improvements, there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate change simulations."

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Handling the physics and/or the parameterization of clouds in climate models remains a central difficulty. There is a needed for increased observations. J. Mitchell highlighted the challenge in a recent paper at the WCRP Workshop on Cloud Properties and Cloud feedbacks in Large-scale Models where he states that "Reducing the uncertainty in cloud-climate feedbacks is one of the toughest challenges facing atmospheric physicists."(see footnote 4)

Cloud modelling is a particularly challenging scientific problem because it involves processes covering a very wide range of space and time scales. For example, cloud systems extending over thousands of kilometers to cloud droplets and aerosols of microscopic size are all important components of the climate system. The time scales of interest can range from hundreds of years (e.g., future equilibrium climates) to fractions of a second (e.g., droplet collisions). This is not to say that all cloud micro-physics must be included in modelling cloud formation and cloud properties, but the demarcation between what must be included and what can be parameterized remains unclear. Clarifying this demarcation and improving both the resulting phenomenological characterizations and parameterizations will depend critically on improved global observations of clouds(see footnote 5) (see also TAR, Section 2.5.5). Of particular importance are observations of cloud structure and distribution against natural patterns of climate variability (e.g., ENSO). Complementing the broad climatologies will be important observations of cloud ice water and liquid water content, radiative heating and optical depth profiles, and precipitation occurrence and cloud geometry.

The recently approved C1oudSat and PICCASO missions, which will fly in formation with the NASA EOS PM (the Aqua Mission), will provide valuable profiles of cloud ice and liquid content, optical depth, cloud type, and aerosol properties. These observations combined with wider swath radiometric data from EOS PM sensors will provide a rich new source of information about the properties of clouds.(see footnote 6)

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And yet, this question of cloud feedback remains open, and it is not clear how it will be answered. Given that the current generation of global climate models represents the Earth in terms of grid-points spaced roughly two hundred kilometers apart, many features observed on smaller scales, such as individual cloud systems and cloud geometry, are not explicitly resolved. Without question, the strategy will for attacking the feedback question will involve comparison of model simulations with appropriate observations on global or local scales. The interplay of observation and models, again, will be the key for progress. Mitchell (same reference states this clearly, "Unless there are stronger links between those making observations and those using climate models, then there is little chance of a reduction in the uncertainty in cloud feedback in the next twenty years." This is echoed in the TAR (Section 7.2.2), "A straightforward approach of mode validation is not sufficient to constrain efficiently the models and a more dedicated approach is needed. It should be favored by a larger availability of satellite measurements."

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PREPARED STATEMENT OF CHARLES F. KENNEL, PH.D.

Good morning, Mr. Chairman and members of the Committee. Thank you for the opportunity to testify. I am Charles Kennel, Director of Scripps Institution of Oceanography, part of the University of California, San Diego. I also serve as Chairman of the National Research Council's Committee on Global Change Research.

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Crucial decisions related to environmental changes are made every day by households, insurance companies, water resource managers, agribusiness executives, public health officials, congress, and countless others. These decisions fundamentally affect our nation's health and its economic and environmental vitality. But the National Research Council's (NRC) Committee on Global Change Research (CGCR) concluded that the information necessary to inform these decisions is not always available.

In its recent report titled "The Science of Regional and Global Change: Putting Knowledge to Work," the CGCR found that the United States' observational and modeling capabilities do not adequately serve society's needs for reliable environmental predictions or precise estimation of ongoing changes. This is in part because the federal government does not have mechanisms to establish and provide resources to key research, observational, and technological endeavors that either cross or transcend individual agency responsibilities.

To solve this problem, the National Research Council recommends establishing a high-level governmental authority to define the national priorities related to global and regional environmental research and decision-making. This authority should ensure and direct adequate resources to those priorities. Without such an authority, agencies will continue to fund only those areas that fall within their purview and the resulting patchwork of observing systems and research will not work as an effective decision-support system.

The progress made over the past decade in understanding global environmental change is substantial, as documented in numerous reports of the NRC and in some of the comments of the other witnesses here this morning. This progress has generally been in understanding the effects of single problems in the environment—such as the effect of carbon dioxide on climate or the effect of acid rain on forests—without considering cumulative effects of multiple factors or the societal context in which the pressures exist. Progress toward sustaining the environmental systems on which life depends is unlikely to be impeded by the individual environmental problems that have occupied the world's attention to date. It is the multiple natural and human factors interacting in a particular location that present the greatest threats and the greatest opportunities. This presents the greatest organizational challenge as well.

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A good example of this is the situation in California. That state, which is currently in the midst of an energy crisis, derives up to a third of its electricity from hydropower. Because of the numerous competing uses for water in California, choices must be made as to whether the rain that falls on the state is diverted for agriculture, lake sustenance, drinking water, flood protection, or river flow for recreation, fish habitat maintenance, as well as electricity generation. These choices can be at odds with one another. The changing natural environment compounds the difficulty of these choices, and better information about the changes is needed to inform the decisions.

In 1998 a strong El Niño led to intense rainfall in parts of California. As a result of climate forecasts in the summer of 1997, water resource managers were able to reduce flood damage and power utilities were able take advantage of the high river flows to maximize hydroelectric production and profits. Coastal communities were also able to prepare for the potentially damaging waves that struck the coast in the winter of 1997/1998 and take steps to blunt their force. Local energy companies altered plans to ensure adequate power supplies and to minimize environmental damage to their facilities. There are other success stories from California. But the picture is not all rosy.

The investment in global change research has led to the limited, but valuable capabilities we have now for short-term climate prediction. The range of estimates from NOAA on the annual return on the investment in the El Niño observing network is between 13–26%, compared to a government goal of 7%. This suggests that even imperfect understanding can add significant economic value to society. But there is much more that remains to be done with even greater promise of payoff. We cannot yet predict the start of an El Niño with precision. However, once it begins, we can identify it and assess its progress. We still have very little idea how the strength or frequency of El Niños might change over the course of the next few decades. There are longer-term processes that operate on decadal to century timescales that we are just beginning to understand and that may impact the El Niño cycle.

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The case of California and the 1997/1998 El Niño is illustrative of the great promise of information relating environmental variability and change to society's needs. Today, seasonal climate forecasts are routinely provided, and used by energy planners, commodities traders, and other sectors of the economy. However, these forecasts are imperfect and have significant uncertainties. In addition, many economic investments must consider time horizons much longer than the 6–9 months covered by today's forecast services. Decisions about energy plants, hydroelectric dams, and other infrastructure components need to consider 10-year outlooks. With continued research and model development, particularly focusing on variations at local and regional scales, we believe significant progress can be made toward providing useful forecasts on such a 10-year horizon.

A new organizing philosophy is needed to reap the benefits of the information revolution and the investments in environmental observations, modeling and research. The NAS recommends organizing around enduring questions as outlined in the NRC report *Global Environmental Change: Research Pathways for the Next Decade;* making a significant investment in modeling, and more closely linking social and natural sciences to examine and understand the multiple stresses interacting in specific areas.

A critical role for the government is to ensure that we have a more comprehensive and sustained observing system and improved modeling capability. The environmental observing "system" available today is a composite of specific, limited systems with no assurance of continuity. The result is insufficient spatial coverage, lack of stability, and poor precision. While these problems do not exist for all environmental variables, they are quite pervasive and inhibit the overall ability of our nation's observations to fully inform decision-making. The other deficient component is our nation's environmental modeling capability. As alluded to in the case of El Niño forecasting, there have been promising developments in the nation's capability to predict climate variations. But the limited availability of computational capacity and the human resources to utilize that capacity for environmental modeling is insufficient. If critical chokepoints in our understanding of global environmental change are to be overcome, the federal government must make a substantial commitment to establishing and maintaining an observing and prediction system that is up to the job.

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The businesses and households of our nation can only gain through the use of better information about environmental variability on local to global scales. The magnitude of the potential gains is illustrated by the fact that nearly 15% of the U.S. GDP originates in climate sensitive industries. To fully realize these gains, the United States must not only improve its modeling and observational capabilities, but it must also forge stronger ties between the physical and social science research communities and the nation's public and private decision makers. These links can be made in part through the establishment of regionally-focused projects that more directly couple environmental research to decision making and that more fully address the multiple interacting and changing environmental factors in those geographic areas. The continuing information revolution can assist in the process of connecting new research results with decision making.

I have not explicitly mentioned human-induced climate change. In my view, defining global change through the narrow focus of the responsibility for greenhouse warming may be obscuring an important opportunity. We may be able to transform the discussion into one that addresses how to capture the potential of the information revolution to structure a science-based end-to-end decision-support system for industry, government, and individuals. The system that is required to extract economic value from environmental information is quite similar, if not identical in many cases, to the system needed to inform policy decisions regarding long-term climate change and the human role in it.

Strong leadership will be required from both Congress and the Executive Branch to establish a new and productive dialogue that helps the nation seize the initiative. New partnerships are needed between physical and social science researchers and decision-makers in government and industry. With the establishment of a high-level governing authority as recommended by the NRC, there will be a focal point for these partnerships. There will be an entity to coordinate global and regional environmental research and decision making and to ensure that adequate resources are directed to the highest-priority issues and that long-term capabilities are sustained.

There is common ground for progress. It will require a new way of thinking. But, let's get started. What we do in the next few years may condition what is possible over the next few generations.

BIOGRAPHY FOR CHARLES F. KENNEL

Charles F. Kennel received an A.B. from Harvard College in 1959, and a Ph.D. in Astrophysical Sciences from Princeton University in 1964. He had been a tenured member of the UCLA Department of Physics since 1967, and was its chairman in 1983–86. He became a member of UCLA's Institute of Geophysics and Planetary Physics in 1971, and was associate director of UCLA's Institute for Plasma Physics and Fusion Research. Dr. Kennel served as Associate Administrator at NASA and Director of Mission to Planet Earth from 1993 to 1996, and in 1996, became Executive Vice Chancellor at UCLA. Dr. Kennel assumed his position as Director, Scripps Institution of Oceanography, Vice Chancellor Marine Sciences, University of California, San Diego in 1998.

Dr. Kennel is author or co-author of over 250 experimental and theoretical publications in plasma physics, space plasma physics, planetary science, astrophysics, and nonlinear science. Kennel has been a Fulbright, Sloan and a Guggenheim scholar, and a Fairchild Professor at the California Institute of Technology. He is a fellow of the American Geophysical Union, the American Physical Society, and the American Association for the Advancement of Science, and a member of the International Academy of Astronautics; the U.S. National Academy of Sciences and the American Academy of Arts and Sciences. Kennel's professional service includes: Chair, Board on Physics and Astronomy, NAS–NRC; Chair, Committee on Solar and Space Physics, Space Science

Board, NAS–NRC; Chair, Division of Plasma Physics, American Physical Society; Chair, Advisory Board, Bartol Research Institute; member, NASA Advisory Council; Chair, Committee on Global Change Research, NRC; Chair, Fusion Sciences Advisory Committee, NRC; Executive Committee, National Advisory Board, Institute for Theoretical Physics, Santa Barbara, NSF; Secretary of Energy's Fusion Policy Advisory Committee, DOE; Advisory Boards: Geophysical Institute, University of Alaska, and Plasma Physics Laboratory, Princeton University; Board of Directors, University Corporation for Atmospheric Research; Member, Visiting Committee, Jet Propulsion Laboratory; and Member, Pew Oceans Commission.

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Dr. Kennel was awarded the Aurelio Peccei Prize from the Accademia Lincei, Rome, and the NASA Distinguished Service Medal in 1996; the James Clark Maxwell Prize from the American Physical Society in 1997; and the Hannes Alfven Prize of the European Geophysical Society in 1998.

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POST-HEARING QUESTIONS

Answers provided by Charles F. Kennel

1. In the near- and long-term, what can or should be done to stabilize existing observational capabilities and to identify crucial variables that are inadequately measured at present? What monitoring capabilities will we lose if we do not take action?

Serious shortcomings exist in both the observational capabilities and the observational strategy of the nation's near- and long-term monitoring approach. The sense of the Committee on Global Change Research (CGCR) is that the responsibility for integrating a comprehensive observing system needs to be given to a high level authority, along with an appropriate level of resources (NRC, 2001a). Climate could be the initial focus of this observing network, building on the existing capabilities, with augmentations to meet other related data needs. The high level authority would continually assess the quality of the overall observing system and address resources to specific needs.

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A management structure is needed for climate and global change research with clearly defined responsibilities that include: (a) decisive strategies for linking observations with modeling efforts (NRC, 2001b); (b) oversight of space-based, ground-based, and airborne networks to ensure that Climate Data Records adhere to the Fundamental Principles of Climate Monitoring (NRC, 2000a); (c) critical judgment on the selection of Benchmark observations that accurately track long-term trends in key climate indices (NRC, 1999a); (d) active engagement of the broader scientific community in the continued innovation of the climate program (NRC, 1998a); (e) encouragement of both the development and the incorporation of new technology into a climate program (NRC, 2001a); and finally; (f) coordinating the U.S. contributions with the broader international observing and research programs (NRC, 2001c).

In terms of long-term climate monitoring, fundamental reconstitution and modernization of the national and global *in-situ* observation networks is needed to provide Climate Data Records (CDRs) and observations (NRC, 1999b; NRC, 2000a). We need to act on the fundamental need for selected Benchmark observations (observations that can be reproduced with defined accuracy at any future time) that accurately specify long-term changes of key climate forcings and responses (NRC, 1999b). Examples include GPS occultations; *in-situ* observations of CO; solar irradiance; and spectrally resolved, absolute radiance emitted to space.

One example of critical capability not currently in place is for inter-calibration of new sensors with outgoing systems so that the integrity of a long-term data record can be maintained. Similarly, there are not consistent standards for evaluating quality of measurements and evolving the system as new discoveries and technologies refine our understanding of what needs to be measured and how best to achieve such measurements (NRC, 2000a).

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In terms of specific observations, the NRC recommends that climate observing requirements be imposed on existing/planned systems, particularly NPOESS (NRC, 2000a and b).

An enhanced CO monitoring network is needed to get a clear understanding of the sources and sinks of carbon around the world (NRC, 1999a). We currently have only 30 sites, which allows the world to be divided into only three regions, making inverse determinations of sources and sinks for individual countries impossible. The interagency "Carbon Cycle Science Plan" poses as one of its two fundamental questions; "what has happened to the carbon dioxide that has already been emitted by human activities?" It asks for "an observational infrastructure capable of accurately measuring net emissions (sources and sinks) of CO from major regions of the earth". It asks for "the capability of early detection of major shifts in carbon cycle function that may lead to rapid release of CO or other unanticipated phenomena." We need to include enough observations and supporting measurements on full ecosystems to understand their responses to natural variability and to anthropogenic stresses (NRC, 2000c). Specifically, we need airborne, space-borne, sea-borne, and ground-based measurements of concentrations and fluxes, and intensive observations and analysis of vegetation cover and activity (NRC, 1999a). Atmospheric chemistry measurements focus on concentrations and fluxes of CO, CH, CO, isotopes, and other tracers, and we need corresponding socioeconomic data such as population, land use, and economic parameters (NRC, 1999a).

As pointed out in part by NRC (1999a) and (2001 d), another critical area where attention is needed is the link between environment and human health related to urban-to-regional nitrates, sulfates, organics, heavy metal and soot sources, sinks and transformation rates. Human health, in many areas of the world, is tightly coupled to the release of oxidants and toxics. I feel that there are three types of pressing problems about the photochemistry of oxidants in the troposphere. The first is the problem of fundamental oxidation pathways. Critical unanswered questions concern the oxidation of organic compounds to stable products, the oxidation of reduced sulfur to sulfates that are central to acidity and to particle formation and growth, the oxidation of nitrogen compounds to nitrates, the direct oxidation of organisms and subsystems of organisms, and the oxidation of biomass. The second issue is the production of infrared active gases that control the Earth's climate. A significant component of this problem centers on ozone in the troposphere, but because of the coupling between chemical and dynamical time constants in this region, the problem involves other species, such as water in all its phases and isotopes, aerosols, methane, and nitrous oxide. A third problem is the control of oxidant export/import across international boundaries; that is, the coupling between regional and global scales.

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Two specific near-term problems are retaining the existing upper air stations and the TAO buoy array (NRC, 1998b; NRC, 2000a).

2. What kinds of things would better computing power allow climate scientists to do that cannot be done now? What are the barriers to improving our computing capabilities? How might the US climate modeling community make more efficient use of its available resources?

The National Research Council recently released a report entitled *"Improving the Effectiveness of U.S. Climate Modeling"* (NRC, 2001b). This is the most comprehensive and timely reflection of NRC views on this subject. The key recommendations of this report are summarized below:

1. Enhanced and stable resources be focused on dedicated and centralized operational activities capable of addressing short-term climate prediction; study of climate variability and predictability on decadal-to-centennial scales; national and international assessments of anthropogenic climate change; assessment of the regional impacts of climatic change.

2. Adopt a policy of open access to systems best suited to climate modeling.

3. Researchers should have improved access to modern, high-end computing facilities connected to the centralized operational activities in Recommendation 1.

4. Climate modeling efforts should be linked to each other and to the research community by a common modeling and data infrastructure.

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5. Research studies on the socio-economic aspects of climate and climate modeling should be undertaken to design the institutional and governmental structures required to provide effective climate services.

NRC (1998c) and NRC (2001 b) concluded that increased computing power would enable more model runs, longer runs, higher resolution models, and more complex runs to refine and improve the models. Bigger and faster computers would enable scientists to resolve ocean eddies (i.e., to have enough detail in the model that the actual movement within ocean eddies can be reproduced). This is a critical component that is not currently incorporated in coupled ocean-atmosphere models. I believe that some of the most important things that could be accomplished with increased computer power would be to 1) increase resolution in existing climate models; 2) incorporate additional processes, especially CO which would allow a consistent projection of future climate in terms of emissions rather than in terms of concentrations; 3) start coupled data assimilation which would allow an analysis of the state of the climate system or show that there is not enough data in certain subsystems to do so; 4) make better seasonal-to-interannual forecasts; 5) improve the design and monitor the performance of measuring systems. Enhanced computational capability would allow models to move to fully couple the atmosphere and ocean with the terrestrial biosphere at a scale that captures the spatial variability in the character of the biosphere and the processes that are important to the biosphere and to human systems.

I believe that there need to be one or more large-scale modeling efforts with sufficient size to make efficient use of computer resources, rather than having many sub-critical efforts scattered around. This must be balanced by an awareness that scientific creativity could be limited if all computational resources are overly concentrated. However, the specific organization of computational capacity is secondary to the fundamental insufficiency of U.S. computational resources.

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3. How many data points from the ocean were incorporated into the IPCC's final analysis and do you believe it to be a sufficient number? Why or why not? How do the number of data points in the ocean compare to the number of data points on land?

This is not a question the CGCR addressed in its deliberations and therefore the following comments are my own views.

All ocean observations available from the World Ocean Atlas produced by the National Oceanographic Data Center of NOAA were used in the IPCC analyses. The atlas contains annual and monthly long-term means for temperature and salinity at multiple depths as well as mixed layer depths as monthly long-term means.

The oceans are not as well measured as the land and atmosphere, either in terms of geographic coverage or frequency of observations, since there is not a comprehensive ocean-observing network from space or in situ sensors. Space observations are essential for providing surface measurements, but cannot provide critical information about conditions at depth as required for numerical ocean circulation models. The Argo Program is an initial effort to sample the subsurface ocean comprehensively. If fully implemented, it would provide 3000 observing platforms floating beneath the surface with the currents. Even this is not nearly enough.

As of now, some places in the ocean, particularly in the Southern Ocean, have never been sampled at depth, and many areas are observed only a few times per year at best. This compares to measurements made four times daily in the atmosphere and on land surfaces. The Southern Ocean is particularly important in ocean circulation and biological productivity. The Partnership for Observation of the Global Oceans announced its "Sao Paulo Declaration" recently, calling on governments of the world to commit resources to "extending ocean observing systems in the Southern Hemisphere, as a minimum requirement towards implementing an integrated strategy for observing the global oceans." Leaders of 22 oceanographic institutions around the world approved this declaration. The Southern Hemisphere has the majority of the world's oceans, but the fewest routine observations, making the achievement of a geographically comprehensive observing system from space and in situ sensors so important.

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4. Would an integrated ocean observing system be useful to climate modelers and result in more accurate models? What physical, human, and fiscal resources are required to build and maintain a multi-decadal climate monitoring network that, 50 years from the present, can with the highest degree of confidence answer the question: ''How has the climate changed?''

Yes, an integrated climate observing system, including ocean, atmosphere, cryosphere, and hydrology is needed (NRC, 1999b). My view is that the ocean component is the most incomplete component at this time. Observations are needed at various depths within the oceans as well as at the surface. Ocean heat content and movement, and ocean carbon are critical climate components that are not yet well understood and need further observations and research.

The worldwide scientific community met in 1999 to outline a comprehensive ocean observing system, assessing what capabilities are already in place and where critical needs had not been met. The resulting plan is available at http://www.bom.gov.au/oceanobs99/

The global ocean data are critical for initialization and assimilation in models and to reveal the physical processes that govern the climate system, enabling improvements in the models. We have not developed comprehensive cost estimates, but currently, in addition to the U.S. operational meteorological satellite system (annual cost approximately $560m), the U.S. is spending approximately $900m on space-based observations to support global change research. I believe that a comparable amount would be needed to develop a comprehensive climate observing network and the associated modeling programs and that a detailed costed design study is urgently needed.

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5. The recent Kyoto negotiations at the Hague were stymied in large part due to disagreements over how efficient plants are at tying up carbon from the atmosphere. Are the current carbon cycle programs sufficient to obtain the understanding we need to that *we can make appropriate policy decisions?*

No. My view is that the existing programs will not provide the needed understanding on a time scale that is consistent with the need for policy decisions. We need coordinated measurements of carbon fluxes, carbon stock changes, and basic biologic processes at a diversity of sites. We also need to understand our capacity to manage the biosphere and we need to have the tools and methods to measure and evaluate our accomplishments. The modeling community needs to be more involved in the Carbon Science Plan as well. The answer to question 1 provides more detail on what observation and research program is needed to improve our understanding of the carbon cycle.

6. The USGCRP is a collaborative multi-agency initiative. How can global climate research be strengthened given the dispersed nature of the initiative? Does the USGCRP umbrella of agencies have a coordinated approach for prioritizing, from a national perspective, their climate modeling research and assessment efforts?

The CGCR report *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1999a), generally referred to as the Pathways Report, lays out the scientific priorities that the USGCRP should address. The more recent CGCR report, *The Science of Regional and Global Change: Putting Knowledge to Work* (NRC, 2001a), provides recommendations on how this problem can be approached, by creating a high level authority with some discretionary resources to take the national perspective and support integrating activities that are not within the purview of individual agencies. Specific recommendations from the latter CGCR report relating to Agency-level actions are summarized below:

1. Ensure an "intimate connection" between research, operational activities, and the support of decision-making.

2. Participate in and support interdisciplinary research relating physical, biological, and human systems.

3. Plan and implement sustained and integrated observing networks and information systems that transcend traditional agency boundaries.

4. Plan to incorporate scientific and technological advances into ongoing research and operational programs.

5. Develop improved models and new predictive capabilities.

6. Develop improved assessment capabilities for integrating scientific knowledge into effective decision support systems.

7. Define and carry out programs of regional and sectoral multiple-stress research and development projects.

8. Connect research, education, and outreach.

7. Are human and fiscal resources allocated effectively to address the above mentioned priorities? Are students being trained to fill either the scientific research positions or the niches of computational science and software engineering required for a successful high-end climate computing capability?

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No, the human and fiscal resources are not effectively allocated. In its recent report (NRC, 2001a) the Committee on Global Change Research states:

The observing "system" available today is a composite of observations that do not provide the information needed nor the continuity in the data to support decisions on critical issues.

The United States today does not have the computational and modeling services needed to serve society's information needs for reliable environmental predictions and projections.

The partnerships between both the physical and social science research communities and public and private decision-makers required to address multiple interacting and changing environmental factors in specific geographic areas do not exist.

The *Pathways* report identifies needs in the research area. In it, the NRC recommends:

1. Research priorities and resource allocations must be reassessed, with the objective of tying available resources directly to the major unanswered Scientific Questions identified in this report. The USGCRP's research strategy should be centered on sharply defined and effectively executed programs and should recognize the essential need for focused observations, both space-based and *in-situ,* to test scientific hypotheses and document change.

2. Observational capability must be developed to support research addressing critical *common themes,* foremost of which are understanding the Earth's carbon and water cycles; characterizing climate change, including the human dimensions component, on temporal and spatial scales relevant to human activities; and elucidating the link among radiation, dynamics, chemistry, and climate.

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3. The strategy for obtaining long-term observations designed to define the magnitude and character of Earth system change must give priority to the most critical Scientific Questions, taking the following into account:

The fact that observing systems have been designed for purposes other than long-term accuracy and that this has undercut the long-term calibration needed for scientific understanding of global change.

Improving the Effectiveness of U.S. Climate Modeling (NRC, 2001b) states that:

"There is. . .a disturbing tendency for decreases at the front end of the employment pipeline, with 1998 showing a 20% drop in the number of Ph.D.s awarded in meteorology and oceanography over 1997 (UCAR Quarterly, Spring 2000), which was not mirrored in other scientific fields."

One of the principal findings of that report is:

". . .There is currently a strain on human resources in the climate modeling community. U.S. modeling groups are having difficulty competing with private industry and with overseas institutions for the high skilled and experienced scientists and computer technologists needed to ensure an effective modeling effort in both research and operational modeling."

Finally, the CGCR report (NRC, 2001a) recommends that agencies "Connect research, education, and outreach," adding that "Fundamental change will be possible only if education and outreach efforts communicate the progress of understanding to all concerned. . .. We need to sustain the nation's supply of scientists, train the people who will manage our environment, alert decision makers, communicate to the public the reasons for decisions, and support a knowledgeable electorate. The quality, diversity, inclusiveness, and timeliness of education and outreach efforts are probably the most important factors determining success or failure in the long run."

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If climate change were a completely natural occurrence and the climatic effect of carbon dioxide from burning fossil fuels turns out not to be so great, what then would the American public get out of the investment in these research programs?

The essence of the recommendations from the Committee on Global Change Research's recent report is to extract both economic and scientific value from an integrated observing system that serves diverse needs, including, but not limited to climate policy (NRC, 2001a). This report finds that, as a society, we need to better understand how the climate system functions, and learn to develop accurate predictive models to enable us to make better decisions. As our global economy creates pressure on global resources, we can benefit from the use of climate forecasts. For example, understanding and predicting the El Niño-Southern Oscillation (ENSO) cycle has already had significant economic and social value. Managing energy resources, forecasting water supplies, assessing risks of forest fires, anticipating severe storms are examples of capabilities that are greatly enhanced by better understanding of climate at global, regional, and local scales. In terms of ocean carbon, improved understanding would enable us to address issues like red tide and changes to the food web. There are already commercial services based on weather forecasting that are worth billions of dollars in terms of commodity markets. I believe that extending this to longer time scales has potentially even more significant economic value.

The overall balance and innovative treatment of observations: the balance between space-based observations and in situ observations, between operational and research observational systems, and between observations and analysis.

The gaps between research and operational observational systems that could threaten needed long-term records.

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The end-to-end responsibility and the principal investigator mode for research observational systems.

4. The restructured national strategy for Earth observations must more aggressively employ technical innovation such as small satellite systems, robotics, microelectronics, and materials to establish a sound balance between *in-situ* ground/ocean-based, airborne, and space-based observations.

5. The USGCRP must revitalize its strategy for the data systems used for global change research to emphasize flexible and innovative systems and provide open access to the scientific community and the public.

6. The USGRCP must foster the development and application of models that can support important policy processes; it must secure adequate computing resources so that large-scale, complex models can be rigorously tested under multiple forcings.

In terms of training and education in climatology, the NRC Board on Atmospheric Sciences (NRC, 1998a) states that:

"Education must be an important facet of the perspective and activities in climate and climate change research entering the twenty-first century. Three elements are of particular importance. First, the general level of public understanding on issues of climate and climate change is disheartening and clearly limits perceptions of the importance of climate research and the development and acceptance of national and international policy. Outreach, contributions to the popular press, and speaking to the general public must be encouraged and rewarded as mechanisms to increase public knowledge of climate and climate change. Second, the long-term health of research programs and their applications depends on strong background in math and science, beginning with K–12 education, and a strong interest in atmospheric, oceanic, and related sciences. . .. Third, we must maintain and strengthen graduate programs oriented toward the critical scientific questions that define limitations in our understanding of climate. Graduate training in climate at universities is best enhanced by (1) added interdisciplinary efforts directed toward climate as a discipline, and (2) educational efforts directed toward increasing the skills required to develop large-scale models of the Earth system and the skills needed to develop and maintain observational systems. Current training is often inadequate because much of the focused effort occurs at national laboratories and other non-university facilities."

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In your testimony, you mentioned the need for a new authority to better coordinate and prioritize climate change research across agencies. Are neither the U.S. Global Change Research Program (USGCRP) nor the Office of Science and Technology Policy (OSTP) performing that function now? What kinds of changes would you make to produce better-coordinated research?

The recent report of the CGCR recommends "the establishment of an institutional arrangement positioned with sufficient authority to coordinate global and regional environmental research and decision making by ensuring adequate resources over the long term and directing them to the highest priority areas." My view is that this authority could be vested in OSTP, although OSTP currently is not assigned this responsibility, nor does OSTP have the critically needed flexible resources to direct to integrative activities. The CGCR report concludes that while the USGCRP attempts to coordinate a collection of individual agency programs, it lacks the authority and resources to direct activities that cut across or fall between the missions and priorities of its individual agency members.

The report states that much new interdisciplinary science was created by the USGCRP. Now, however, is the time to build a sustained observing infrastructure based on our new interdisciplinary thinking. The challenge now is not just to better coordinate research, but to inspire and facilitate innovative and integrative research that is addressed to key national priorities without regard to the individual mandates and missions of the individual agencies. The agency-based activity must be continued and provides a fundamental basis for what is now needed at the national level. It is necessary now, but not sufficient. However, broad, crosscutting infrastructure in observations and computation is still not in place and there is no easy process for high-level assessment of needs and priorities.

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The goal now is to enable science to better support policy and economic decision-making at international, national, and regional levels. In my view the budgetary fragmentation across different OMB examiners and different congressional committees is also a persistent obstacle to a truly integrated program that mirrors the fragmentation of agency programs. The proposed high level authority should address these problems.

NRC, 1998a. *The Atmospheric Sciences: Entering the Twenty-First Century.* 364 pp.

NRC, 1998b. *A Scientific Strategy for U.S. Participation in the GOALS Component of the CLIVAR Programme.* 69 pp.

NRC, 1998c. *Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities.* 65 pp.

NRC, 1999a. *Global Environmental Change: Research Pathways for the Next Decade.* 595 pp.

NRC, 1999b. *Adequacy of Climate Observing Systems.* 51 pp.

NRC, 2000a. *Improving Atmospheric Temperature Monitoring Capabilities.* 17 pp.

NRC, 2000b. *Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites.* 51 pp.

NRC, 2000c. *Global Change Ecosystems Research.* 48 pp.

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NRC, 2001a. *The Science of Regional and Global Change: Putting Knowledge to Work.* 19 pp.

NRC, 2001b. *Improving the Effectiveness of U.S. Climate Modeling.* 128 pp.

NRC, 2001c. *Comments on Catalyzing U.S. World Climate Research Programme Activities.* 21 pp.

NRC, 2001d. *Global Air Quality: An Imperative for Long-Term Observational Strategies.* 41 pp.

All of these reports, except NRC (1998a) and (2000c), can be obtained by Congressional staff free of charge by contacting Karen Elliott (*kelliott*@nas.edu or 202–334–3511). All NRC reports can be read and purchased at: *http://www.nap.edu*

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APPENDIX 4: Additional Material for the Record

Von Gugelberg Memorial Lecture on the Environment

STANFORD LECTURE

SIR JOHN BROWNE, GROUP CHIEF EXECUTIVE

6TH MARCH, 2001

Ladies and Gentlemen, good afternoon.

It's a pleasure to be back in Stanford and a great honour to be invited to deliver a lecture in this very distinguished series.

The title of this lecture is "A progress report" and I think that is very appropriate.

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I think it very important to establish the belief that this is an issue on which progress can be made—because there is some quarters, in some parts of the world a kind of fatalism which says that the environmental challenges we all face are intractable.

That makes people either try to deny that there is a problem. . .or to say that the problem is so great that we have to retreat from the process of economic development and abandon the aspiration of improving living standards.

I want to try and show that those two alternatives are both wrong.

I want to try and show that progress is possible.

But the title has another implication too—this is a report about work in progress—not about something that is finished and done.

There is much to do, and I want to talk about that as well.

And finally the title implies a factual and businesslike approach -which is in my view just what we need.

The environment is an issue which arouses huge emotion.

That is very understandable. People worry and feel angry. . .but if we're ever going to make progress those concerns have to need to be subjected to a rational analysis.

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I think the progress report has to start with reality and with some facts.

The first reality is the growth of the world's population. Up by 160 percent in my lifetime from 2.5 bn to 6 bn, and rising now by 90 million a year which means that enough people are born every 48 hours to populate a city the size of San Francisco.

And every one of those people needs energy.

To me, the instinct not just to survive, but to strive for a better life and to try to improve your living standards, is fundamental to human nature.

And to do that—to have food, to have a home, to have light and heat and mobility even at the most basic level—requires energy. Energy is what keeps people alive, and what allows them to live with some element of dignity.

That is the second reality.

The third is that for the foreseeable future the bulk of the energy the world needs will come from hydrocarbons and particular from oil and gas.

That isn't an assertion on behalf of the oil and gas industry. It's a simple fact.

Oil and gas currently supply 65 percent of the world's daily needs and over the next two decades at least that figure will increase. Nuclear power remains expensive, particularly if you include the full costs of disposing of the waste products. Coal is still important in some areas but it carries enormous environmental costs in terms of emissions. In the main energy using activities—in transportation, industry, domestic supply, and power generation—the most convenient fuels in every sense are oil and gas.

Today we use over 75mb/d of oil and 220 bcf/d of gas.

By the end of this decade on pretty conservative assumptions about economic growth the world will use more than 90 mm bbl of oil and 280 bcf/d of gas. And those figures will still be rising.

What about renewables and hydrogen? Aren't they the answer?

One day they may well be part of the answer, and given the scale of the need for energy we believe it is prudent to start developing them as viable additional sources.

This will require co-ordinated action by governments, consumers and companies in the private sector. We need to achieve the necessary economies of scale to ensure that early investment is worthwhile, and that the resulting energy prices are attractive to consumers.

Currently renewable energy, excluding the large-scale hydro plants, represents only 1 percent of primary energy production worldwide, and 2 percent of global electricity generating capacity.

At the moment renewable energy is dominated by small scale hydro projects and biomass but in the future other sources will play a bigger role in fuelling at least a small part of the growth in electricity consumption over the next 20 years which some predict to be as much as 80 percent.

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We, and others are doing significant work on the technology of photovoltaics—solar power.

We're also developing the use of hydrogen as the ultimate clean source of fuel for vehicles. Hydrogen wouldn't generate any tail pipe emissions—except for water of drinking quality standard.

We have partnerships with Ford and GM and Daimler Chrysler to promote the use of experimental hydrogen powered fuel cell vehicles in London, Sacramento, Sydney and Beijing, and a project with BMW to demonstrate the benefits of using hydrogen in conventional internal combustion vehicles.

Within the next two years we'll begin supplying hydrogen from our refinery at Kwinana in Australia and we aim to have one of the world's first hydrogen retail stations.

Those are very exciting developments, and of course many other companies are also investing and making progress in this area.

But these are experiments with future potential. They shouldn't take our eyes off the current reality which is that the world will continue to rely on oil and gas for a very long time to come.

Supplies are available to meet that demand.

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On the best estimates the world has found and produced around 800 bn barrels of oil and natural gas liquids. The remaining reserves are around 950 bn barrels much of which is in the Middle East. However we believe that there are another 500 bn barrels of additional supplies which can come from new discoveries and improvements in the recovery rates in existing fields.

Outside the Middle East, quite a large proportion of the oil still to be found and developed in the deep water beyond the continental shelf, but technology is making the deep water accessible in ways that seemed impossible only ten or fifteen years ago.

In terms of natural gas the figures are much larger—only some 20 percent of estimated world total natural gas supplies have so far been found and produced and huge supplies remain in many different parts of the world.

So leaving aside politics, there need be no shortage of oil and gas.

But the fourth reality is that the growing consumption of oil and gas poses an environmental challenge.

At one level there is the challenge of low level pollution, and poor air quality particularly in the cities.

And longer term there is the risk of climate change through global warming.

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Of course the science of climate change remains unproven, but no one reading the latest scientific reports published by the IPCC over the last few weeks could ignore the mounting evidence of a link between human activity and the world's climate or the implications.

The latest report concentrates on the likely consequences.

Rising water levels which put particular communities at risk and floods in some areas matched by drought and a decline in long term water levels which risks disrupting agricultural systems and adding to the problems of some of the world's poorest areas.

To put that in another perspective—a recent report by the insurance industry has estimated that the damage could cost the global economy over $300 bn a year.

And those four points represent the reality.

Of course that isn't a comfortable analysis, for the world or for the industry of which I'm part because it implies that the status quo won't continue as it is, and that some change is necessary.

If that is the reality, what can we do about it—how can we make progress? And what can business do?

Well the purpose of business is to do business. To make profitable investments, and to deliver competitive returns on behalf of our shareholders.

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That is a very simple purpose—clear and limited.

We don't exist to run the world, and we have no legitimacy to do so.

We can't take decisions for people—because we have no authority. No one elected us.

Clearly, companies are part of society. We fulfill a specific role on behalf of society—

creating wealth and meeting needs. But we're not responsible for society.

We have a single simple purpose.

But, of course that purpose can't be fulfilled in isolation. No company, however big, is sufficient unto itself.

A company's ability to fulfill its purpose depends on the decisions and choices made every day by all the people with whom they do business—Governments, other companies, staff and, in our case, the ten million or so people who buy things from us around the world every day.

Our ability to do business is determined by our capacity to meet the needs of those people, and those needs in turn are being set by the reality I've described.

I believe the challenge—the business challenge—is to transcend the sharp trade off implied by what I've said.

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Put in the simplest terms the trade off is that the world has a choice—economic growth, fueled by increasing energy consumption. . .or a clean environment. We can have one or the other, but not both.

If that is the trade off, it is unacceptable. People want both.

And I believe there is a huge commercial prize for those who can offer better choice which transcend the trade-off.

And that was the objective we set ourselves four years ago, when I gave a speech here at Stanford which said that some action, of a precautionary nature, particularly on climate change, was essential.

If no precautionary steps were taken then drastic action might become necessary, which could be extremely disruptive to the world's economy.

That was quite an occasion—a speech given outside in the Frost auditorium on a beautiful sunny day. A speech which expressed a change of policy for the first time in public, and which was the culmination of an enormous amount of internal thought and preparation.

Four years on, this seems the right moment and the right place to review what we aimed to against the reality of the track record. A good moment to see if the aspiration is justified.

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I'll talk about BP, but I think its important to make clear that there are many people looking for ways to transcend the trade off, and this isn't an isolated story.

Many of things we've achieved couldn't have been done without the help of our partners and contractors and suppliers. So the focus simply reflects the fact that this is the only story I'm really qualified to tell.

We set ourselves a number of goals.

First, the objective of reducing our own emissions of carbon dioxide by an absolute amount of 10 percent from a 1990 base, while growing the company.

We've made good progress. By the end of last year we had delivered a reduction of 5 percent and we can identify at least another 5 percent which is deliverable over the next three years.

The progress we've made hasn't come from the use of a single magic bullet—just dozens and dozens of initiatives—most of them undertaken at local level by our business unit leaders and their teams.

Reducing flaring; tightening the control of emissions from our refineries; reducing our own energy use. They all count. Let me quote just two examples.

In our acetic acid production unit in the UK we found that we were producing less acetic acid for the volume of carbon monoxide being used than should have been the case.

We traced the problem to a leak from the compressors.

A new advanced sealing process was created by the engineers and the result was an increase in production of acetic acid of 20,000 tonnes a year, and reduction of 15,000 tonnes year in the emissions of Carbon Dioxide—a reduction of 98 percent with all the benefits that brings both in terms of atmospheric pollution and health and safety in the plant.

Or another example.

In the U.S. venting accounts for almost 60 percent of all the methane which is emitted by our gas business in the Western states. To reduce that, we have a project underway to control emissions from all wells in the areas of the Greater Green River and the San Juan basin.

This is not an easy project, but we've now found that with an investment of $1.4 million we can save more than 20,000 tonnes of methane a year, which has the greenhouse effect of nearly half a million tonnes of Carbon Dioxide.

And of course the methane can now be sold—turning what began as an environmental project into something that is also good profitable business.

Reducing emissions was the first goal. The second was to demonstrate that we could create an internal trading system which would allow us to meet our target at the lowest possible cost by allocating the resources to the places where they would have most effect.

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Meeting the target not by requiring everyone to cut emissions by 10 percent, but by putting a monetary value on each unit and encouraging the whole internal team to cooperate in delivering the target at the lowest cost.

Our emissions trading system began in 1999, and has been working across the whole company since January 2000. In the first year 2.7 million tonnes carbon dioxide were traded at an average price of $7.6 per tonne.

The system now covers every single operation we have around the world.

We've learnt a lot, and now we're ready to develop the system and perhaps to bring in third parties which will allow us both to have a greater impact and to reduce unit costs.

This approach has encouraged our business units to look for innovative, cost effective ways of meeting the target.

The third goal was to make a positive contribution to the problem of air quality.

We have developed a series of clean fuels—gasoline and diesel without lead, sulfur or benzene. That programme was launched in January 1999.

By the end of last year it had reached 59 cities worldwide. By the end of this year those products will be available in 90 cities, including many where there are series and persistent air quality problems.

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We'll continue to extend the reach of that programme and to work on the technology so that we can provide even cleaner fuels. And we'll work with the car companies and others who share our view that the wonderful achievement of individual mobility—one of the great advances of the last hundred years—doesn't have to be compromised and tarnished by pollution.

And the fourth goal was to make a contribution to the shift in the energy mix. That mix is always changing.

There has been a shift, worldwide over the last fifty years, from coal to oil, and now there is a further shift going on in favour of natural gas. We are part of that process.

Five years ago natural gas represented no more than 15 percent of our production. Now its 40 percent and still rising. Not just in the developed world—where we're the largest producer in the United States—but in areas where energy demand is growing most rapidly and where the choice of supply to meet that demand will have huge environmental consequences.

In China, for instance, we intend to be a major supplier of natural gas—helping the country to escape from a dependence on coal.

All the things I've mentioned are work in progress.

It is far too early to celebrate victory.

But I believe that we've demonstrated that it is possible to combine economic growth with a progressive improvement in the environmental impact of that growth.

There is much more to do, but on the basis of the track record so far there is room for cautious optimism—which is an all too rare commodity in the environmental debate which is still, too often reduced to slogans and denial.

But, of course, just as no company stands alone; so no single company on its own can do everything that is necessary around the world.

Progress depends on the cooperation of different elements of society if there is to be a material change.

This is where pessimism seems to have taken over the debate.

There is a sense that the limited progress made since Kyoto indicates that cooperation is impossible.

I don't agree. Here again I think there are grounds for cautious optimism.

First because Kyoto was just one stage in the process of discussion—not an end point.

I think we can usefully compare the debate on the long-term issue of climate change to the debates on free trade from the initial establishment of GATT or the debate on disarmament which has been running since the early treaties of the post war period.

Both took half a century, and both are still incomplete—but through successive steps they both made great progress. And that I think is how this debate will proceed. Not through one-step to a perfect solution, but through one step to another step.

Linked to that, the second reason for optimism is the technical progress that has been made—in the academic world, and in the business community. Progress in understanding the problems in detail and in offering answers.

An important part of that is the success of the trading efforts that have been initiated by us, and by others, and the potential which trading offers to remove the fear that the cost of dealing with this problem was unmanageable and that any action would cost enormous numbers of jobs.

One of the most interesting studies published in the last few months was the report from the Pew Centre which showed that the cost of reducing emissions to the Kyoto target levels could be cut from an estimated $57 bn a year to less than $9 bn if a global trading system were used to allocate resources, and by $20 bn to $37 bn even if the trading system just embraced annex 1 countries. I imagine that there still significant savings even if the trading system is established just within individual countries.

The fourth reason for optimism is the approach of some key Governments, who I think have begun to appreciate the value of incentives and non-prescriptive regulation. Around the world I think that constructive approach is having a real impact—encouraging a shift in the fuel mix and a move to cleaner fuels in industry and transportation.

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So cautious optimism—supported by the advances in technology and by the practical use of public power.

And underpinned by one other factor—globalasation.

I know that in some circles globalasation is much abused and regarded as the source of every problem we face.

Globalization is a complex and incomplete process but I don't think that anyone who cares about the environment could seriously regard its impact as negative.

Quite the reverse.

Most of the advances I've talk about flow from the spread of knowledge which is the unique characteristic of globalasation.

Knowledge of the challenge, and knowledge of the potential solutions.

Knowledge of the challenge, and knowledge of the potential solutions.

Knowledge which is transmitted not just in the public domain—in the media—but also knowledge which is transmitted through particular networks—within the academic world, and within companies.

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Almost all the steps we've taken for instance to reduce emissions began with a particular advance in a particular place. They have spread and become common practice because we have networks within the company—technical specialists sharing experience and ideas on a worldwide basis, and able to do so in real time because of the advances in communications.

When you see it in action that is a magical process, and it reminds of what is becoming possible as globalasation creates a single community of knowledge. And that is just what is needed to make progress.

So, Ladies and Gentlemen that is the progress report. A good beginning, much to do but most important of all sufficient grounds for cautious optimism—based on what look like practical advances and real progress.

If we can build on what has already been achieved in that spirit we can confront the problems and help to create and spread the solutions. Not with a single silver bullet—but with a whole series of humdrum local steps which cumulatively make a real difference. That is the role of business. Progress not through drama, but through practical delivery.

The answer to the environmental challenge of economic growth is neither denial nor retreat. The answer is not to say there isn't a problem or that the problem is so intractable that we have to put a halt to the whole process of economic advance.

The answer lies in allowing and encouraging the process of economic development to resolve its own contradictions. The paradox is that the answer to the problems created by development lies in more development. That has been the story of human progress so far, and I believe we are now seeing that story rewritten again.

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Thank you very much.

If you have a question or comment about bp world please go to the *Help section* and use the online feedback form there.

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(Footnote 1 return)
Last year, however, the National Academy of Sciences issued a report concluding that measurements taken at the Earth's surface do in fact show that the temperature of the surface of the Earth is rising, and that satellites, which measure the temperature of the lower to mid-troposphere (the layer of air up to 8 kilometers above the Earth), do not necessarily contradict those surface measurements. The Academy suggested that the actual layer of the troposphere measured by the satellites may be warming less than the surface of the planet, but recommended further research to better determine if this is in fact the case.

(Footnote 2 return)
See attached "Verbal Remarks of Daniel Albritton, Director, Aeronomy Laboratory" (in Appendix 1).

(Footnote 3 return)
See letter from Dr. Moore revising his response to this question (in Appendix 1).

(Footnote 4 return)
Mitchell, J. 2000. Modelling cloud-climate feedbacks in predictions of human-induced climate change. In: Workshop on Cloud Processes and Cloud Feedbacks in Large-scale Modes. World Climate Research Programme. WCRP–110; WMO/TD–No. 993. Geneva.

(Footnote 5 return)
Senior, C.A., 1999. Comparison of mechanisms of cloud-climate feedbacks in a GCM. *J. Clim.*, 12, 1480–1489.

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