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ABSTRACT

Increased levels of carbon dioxide have contributed to the problematic phenomenon known as the greenhouse effect. Evidence has indicated that the rise in carbon dioxide levels could be accurately correlated with a rise in the Earth's mean temperature, a shrinking of the polar icecaps, and a resulting rise in the Earth's mean sea level. The problems resulting from this situation are reviewed in these proceedings. Individuals presenting testimony and/or providing prepared statements (and when applicable, supporting documentation) include: Carl Sagan; John Trabalka; Wallace Broecker; William Jenkins; John Hoffman; Thomas Malone; Rafe Pomerance; and James Kane. Topic areas disucssed are: (1) climate sensitivity; (2) carbon dioxide's effect on crops; (3) role of the oceans and rise in sea level; and (4) preindustrial carbon dioxide levels. A research timetable and program strategies are presented for reducing the greenhouse effect. One of the strategies emphasized by the Department of Energy is the expansion of a basic knowledge based on carbon dioxide buildup. It is recommended that data collection in this area precede impact assessments, plans, and policy options. (ML)

CARBON DIOXIDE AND THE GREENHOUSE EFFECT

HEARING

BEFORE THE

SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT

AND THE

SUBCOMMITTEE ON NATURAL RESOURCES, AGRICULTURE RESEARCH AND ENVIRONMENT

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY U.S. HOUSE OF REPRESENTATIVES

NINETY-EIGHTH CONGRESS

SECOND SESSION

FEBRUARY 28, 1984

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CARBON DIOXIDE AND THE GREENHOUSE EFFECT

TUESDAY, FEBRUARY 28, 1984

HOUSE OF REPRESENTATIVES, COMMITTEE ON SCIENCE AND TECHNOLOGY, SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT, AND SUBCOMMITTEE ON NATURAL RESOURCES, AGRICULTURE RESEARCH, AND ENVIRONMENT,
Washington, DC.

The subcommittees met, pursuant to notice, at 9:40 a.m., in room 2218, Rayburn House Office Building, Hon. Albert Gore, Jr. (chairman of the Subcommittee on Investigations and Oversight) presiding.

Present: Representatives Gore, Scheuer, Volkmer, Reid, McGrath, Skeen, Schneider, and Lewis.

Mr. GORE. The subcommittees will come to order.

I would like to welcome all of our witnesses and guests today. This is the latest in a series of hearings that our two subcommittees have been having on the greenhouse effect.

One of the observations that some of us on the Science and Technology Committee have been making recently has been the increasing evidence that science and technology are presenting our society with social and political challenges unlike any we have ever confronted in the past. The way we live is inevitably going to be altered by our technological creations and by the increased knowledge we derive from the healthy scientific enterprise that we sponsor in this country. Thus, as legislators, we have a responsibility to keep up to date, and try and anticipate problems, rather than waiting for a disaster to be sprung upon us.

Such is the case with the subject we are here to discuss today. The greenhouse effect is a precise example of how our increased knowledge is really laying a new problem at our doorstep and, moreover, it shows how our scientific enterprise can give us bad news where one cannot help musing that some information we wish that we didn't know.

The greenhouse effect in some respects seems more like a bad science fiction novel than a critical issue deserving public policy review of the highest order. Indeed, some still find it difficult to discuss this issue in a totally rational way, in view of its almost unthinkable potential. Can we really imagine a New York City with the climate of Palm Beach, a Kansas resembling central Mexico, or 40 percent of Florida under water? It's difficult.

Given the serious, indeed the potentially drastic impacts of this scenario, however, it is critical that the Government research this problem to its fullest, for this is not a problem to be ignored. Moreover, if we simply put off critical challenges, we often find out later that it's too late to act.

For this reason, my colleague and good friend, Jim Scheuer, who chairs the Subcommittee on Natural Resources, Agriculture Research and Environment and I have made this phenomenon a priority, along with our the ranking member, Joe Skeen, and the membership of the two subcommittees.

We had first explained the serious nature of this problem in July 1981, when a number of prominent scientists, notably Roger Revelle, gave us their opinion that the greenhouse effect was not a theoretical entity, but a real phenomenon.

In April 1982, when we revisited the issue, the message that we heard was even more troubling. First, the evidence was made clear by Nobel laureate Dr. Melvin Calvin that the greenhouse effect was no longer just a pet theory of a few, but rather that its existence had become the subject of a scientific consensus.

This viewpoint was buttressed by evidence presented by James Hansen and George Kukla that the rise in CO_2 levels could be correlated rather precisely with a rise in the Earth's mean temperature, a shrinking of the polar icecaps, and a resulting rise in the Earth's mean sea level. At that time the Washington Post adequately described the situation when they penned an editorial that stated the greenhouse effect was no longer just something for the "sandals and granola" crowd. It was in the mainstream of scientific thought.

The newest questions in our examination of this issue then became: When can we expect to see the impacts of this phenomenon? How severe will those impacts be? And how should we proceed from here in our research program? These are the essential questions we hope to put to the scientific community today.

In terms of the impact of the greenhouse effect, we will hear today from the National Academy of Sciences and the Environmental Protection Agency on two important reports that they have issued in between our last hearing and this hearing. These reports are important, in that they represent the first attempts to calculate exactly what the impacts of the greenhouse effect will be, and when they will be felt.

EPA predicts that we will experience a rise in temperature in the neighborhood of 3.6 degrees Fahrenheit by the year 2040, and a rise of as much as 9 degrees Fahrenheit by the year 2100. An earlier study by the same group projected that we could experience sea level increases ranging from 4.5 to 7 feet by the end of the next century.

Even given the EPA's rather significant impacts, their postulations about how we could slow down or mitigate the impact of the greenhouse effect were even more dire. They essentially concluded that there were, and are, no reasonable policy options available to slow down this phenomenon.

The National Academy of Sciences was more optimistic. While they predicted a 2- to 8-degree Fahrenheit rise in temperature and a 2.5-foot rise in sea levels by the year 2100, they were far more comforting in that they pointed out that there are a number of mitigating factors, such as reforestation and the ocean systems, which will either slow down the impacts, or at least make them less dislocating.

Today we will also hear from a panel of noted scientists that the role of the oceans is a major unknown in the Earth's atmospheric scheme. While we had once thought that the ocean might absorb much of the heat created by a CO_2 buildup, some prestigious researchers in this discipline will tell us today that perhaps those assumptions about our ocean systems were dead wrong, and that the oceans, ironically because of the greenhouse effect, may be losing their ability to stop the harm. In this respect the greenhouse effect is both its own cause and effect.

Lastly, we will begin today to review the Department of Energy's research program. Regardless of how dire one's viewpoint might be, it is inarguably true that now is the time to begin deciding what questions need to be asked and how we should go about answering them.

A few months ago I was asked to explain my own concern about the greenhouse effect. My response was that, like many others, I have children and hope to have grandchildren. I think that we owe our grandchildren the opportunity to live in this country and in a society resembling the one we now have, if not better. We all owe it to our future generations to reduce the uncertainties and find a solution to this problem of CO_2 buildup. It is in this spirit that we will conduct these proceedings today.

Now I would like to call on the cochairman for these hearings, Congressman Jim Scheuer.

Mr. SCHEUER. I thank you, Mr. Chairman.

I have an eloquent statement of soaring beauty but I don't think it can match with the statement we are going to hear from Carl Sagan, who is our first witness. So I would ask unanimous consent to insert my statement in the record for the benefit of your grandchildren who are soon to come and my first grandchild who came a week ago. [Laughter.]

Mr. GORE. Oh, great. Without objection, we'll do just that.

[The opening statement of Mr. Scheuer follows:]

STATEMENT OF THE
HONORABLE JAMES H. SCHEUER, CHAIRMAN
SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURE RESEARCH AND ENVIRONMENT

FEBRUARY 28, 1984

THANK YOU, MR. CHAIRMAN.

IN THIS CENTURY MAN HAS ACQUIRED THE POWER TO CATASTROPHICALLY MODIFY THE FRAGILE ATMOSPHERE OF OUR PLANET.

IN CONTRAST TO THE CATACLYSMIC EFFECTS OF A MAJOR EXCHANGE OF NUCLEAR WEAPONS ON THE ENVIRONMENT, THE BUILD UP OF CARBON DIOXIDE AND OTHER TRACE GASES IS EXPECTED TO RESULT IN SLOW BUT INEXORABLE CHANGE IN CLIMATE.

THE RESULTS OF BOTH, HOWEVER, MAY BE EQUALLY DISASTROUS.

INCREASING LEVELS OF CARBON DIOXIDE CAUSE HEATING OF THE EARTH'S ATMOSPHERE BY TRAPPING ADDITIONAL SOLAR RADIATION, A PHENOMENON KNOWN AS THE "GREENHOUSE EFFECT".

THIS EFFECT HAS BEEN MODELED WITH STEADILY IMPROVING REALISM FOR MORE THAN A CENTURY.

BUT TODAY'S WORST CASE SCENARIOS GIVE US ONLY A FEW DECADES TO RESPOND TO THESE INSIDIOUS CHANGES IN OUR ENVIRONMENT IF WE ARE TO AVOID MAJOR ECONOMIC AND SOCIAL REPERCUSSIONS.

THE POTENTIAL IMPACT IS STAGGERING.

ACCORDING TO A RECENT NATIONAL ACADEMY OF SCIENCES REPORT, SEVERE REDUCTIONS IN WATER RUNOFF INTO THE MISSOURI, RIO GRANDE AND LOWER COLORADO WATER REGIONS ARE A REALISTIC SCENARIO FOR THE NEXT CENTURY.

CROP YIELDS IN THE MID-WEST MAY DROP SIGNIFICANTLY IN THE WARMER, DRIER CLIMATE.

THE SEA LEVEL MAY RISE BY OVER TWO FEET, OR, ACCORDING TO A RECENT EPA REPORT, BY OVER TEN FEET.

IF SUCH PROJECTIONS ARE EVEN APPROXIMATELY CORRECT, THEN WE NEED TO HAVE ACCURATE AND RELIABLE DATA NOW.

DECADES ARE REQUIRED TO PLAN AND IMPLEMENT THE IMPLIED MAJOR CHANGES TO THE INFRASTRUCTURE OF OUR COASTAL CITIES AND INDUSTRIAL PROGRAMS.

IS OUR RESEARCH PROGRAM ADEQUATE TO MEET OUR NEEDS?

THE ADMINISTRATION APPEARS TO BELIEVE SO.

HOWEVER, THE DEPARTMENT OF ENERGY BUDGET REQUEST FOR THE CARBON DIOXIDE PROGRAM IS ONLY $13.4 M, AN INCREASE OF A MERE $0.9 M (7%) OVER THE FY 84 APPROPRIATION.

YET A RECENT EPA REPORT CONCLUDES THAT "CHANGES BY THE END OF THE 21ST CENTURY COULD BE CATASTROPIC TAKEN IN CONTEXT OF TODAY'S WORLD", AND THAT "A SENSE OF URGENCY SHOULD UNDERLIE OUR RESPONSE TO THE GREENHOUSE EFFECT".

THE REQUESTED FUNDING LEVELS ARE INCONSISTENT WITH THESE CONCLUSIONS.

FURTHERMORE, THEY ARE NEGLIGIBLE RELATIVE TO THE COSTS OF CONTINUING TO APPROACH THE PROBLEM OF CHANGING CLIMATE CONDITIONS IN A FRAGMENTED AND DISORGANIZED FASHION.

TODAY'S HEARING WILL EXAMINE RECENT RESEARCH RESULTS WHICH HAVE ADVANCED OUR KNOWLEDGE AND WHICH HAVE DEMONSTRATED HOW LITTLE WE KNOW ABOUT SOME OF THE CRITICAL ELEMENTS OF CLIMATE CHANGE.

WE SHALL ALSO HEAR FROM OFFICIALS OF THE DEPARTMENT OF ENERGY.

THEY WILL ADDRESS THE PRESIDENT'S BUDGET REQUEST FOR THE CARBON DIOXIDE PROGRAM FOR 1985 AND THE CHANGES IN THE PROGRAM'S SCOPE AND DIRECTION.

Mr. GORE. I would like to recognize my colleague, the ranking minority member of the Investigations Subcommittee, Joe Skeen.

Mr. SKEEN. Thank you, Mr. Gore, and thank you, Mr. Scheuer. I will concur with Mr. Scheuer's observation, and also in the interest of this grandson who was born July 11, and my first. I would rather listen to the distinguished leader of the panel we have today.

I do want to say, however, this is a very serious topic. I want to congratulate you two for your continued interest and the emphasis that you have given to this important issue. Thank you very much, Mr. Chairman.

[The opening statement of Mr. McGrath follows:]

HONORABLE RAYMOND J. MCGRATH

HEARING ON CARBON DIOXIDE AND THE GREENHOUSE EFFECT

FEBRUARY 28, 1984

I WANT TO JOIN THE CHAIRMEN IN WELCOMING OUR WITNESSES HERE THIS MORNING.

AS IS THE CASE WITH ACID RAIN AND POLLUTION OF OUR LAKES, RIVERS AND OCEANS, INCREASING CO_2 IN THE ATMOSPHERE REPRESENTS A PROBLEM OF GLOBAL PROPORTIONS. WE CANNOT OVERLOOK THE RELATIONSHIP BETWEEN DECISIONS WE MAKE NOW REGARDING THE ATMOSPHERIC SITUATION AND WHAT WILL HAPPEN ONE OR TWO OR THREE OR MAYBE EVEN FOUR DECADES FROM NOW. SUCH IS THE DILEMMA OF ALL OF OUR ENVIRONMENTAL CONCERNS.

WE ARE CONSTANTLY LOOKING TO SCIENCE FOR THE GUIDELINES UPON WHICH WE BASE OUR LEGISLATIVE ACTION. YET, THE TIME CONSTRAINTS UNDER WHICH SCIENCE AND THE CONGRESS WORK DO NOT ALWAYS COMPLEMENT ONE ANOTHER.

FOR SCIENCE TO WORK EFFICIENTLY, HYPOTHESES MUST BE TESTED AND RETESTED BEFORE A THEORY IS CONFIRMED. IN CONTRAST, WE HERE IN CONGRESS ARE OFTEN CONFRONTED WITH DEMANDS FROM OUR CONSTITUENTS FOR IMMEDIATE ACTION ON ENVIRONMENTAL THREATS.

I THINK WE CAN SAFELY SAY THAT THERE IS A SCIENTIFIC CONSENSUS THAT A CO_2-INDUCED CHANGE CAN BE EXPECTED. THE UNCERTAINTIES SEEM TO FOCUS ON <u>WHEN</u> THE CHANGE WILL OCCUR, <u>WHERE</u> IT WILL OCCUR, AND <u>HOW LARGE</u> IT WILL BE.

WE NEED TO INSURE THAT OUR RESEARCH IN CO_2 IS FUNDED ADEQUATELY AND FOCUSED ON AREAS WHICH WILL LEAD TO REDUCTIONS IN THESE UNCERTAINTIES. I LOOK FORWARD TO RECEIVING THE RESEARCH RECOMMENDATIONS OF OUR DISTINGUISHED WITNESSES.

Mr. GORE. Well, thank you. Let's just call our first witness, then. We are very honored to have Dr. Carl Sagan from Cornell University and other parts as well. We, the subcommittees, are indebted to you, Dr. Sagan, for agreeing to take a great deal of your valuable time to review some of the existing literature on this problem, and utilizing your well-known and, in my view, rather extraordinary talents for putting science in a perspective that us lay people can understand helping us to sort through this problem. We really appreciate the amount of time that you have spent on it, and without further ado I would like to call on you at this time. Welcome.

STATEMENT OF DR. CARL SAGAN, LABORATORY FOR PLANETARY STUDIES, CORNELL UNIVERSITY

Dr. SAGAN. Thank you, Congressman Gore. I am pleased to be here in more ways than one. It was a long flight.

Let me begin by saying that what I will try to give is a general perspective on this problem. The other panelists and witnesses will, I gather, give a detailed description of the recent EPA and National Academy studies, and they are much more qualified to do that than I am.

But what I would like to do is, first of all, provide some assurance that there is such a thing as a greenhouse effect and that it can be serious, and at the end of my remarks to say something about the general question of constantly stumbling upon new potential catastrophes of climatic and other sorts, and the question of what, if anything, can be done at least to keep a little bit ahead in this sequence of potential catastrophes that seem to be discovered, one every few years.

If you imagine a planet which has no atmosphere and no clouds, what determines the surface temperature? Well, in principle there would be two sources of energy. There might be internal energy coming up from the inside of the planet—this is certainly true for Jupiter, for example, to a significant degree—and there is energy coming from the outside, and that is almost entirely from the Sun.

In the case of the Earth and the inner planets, there is no significant energy coming from the inside, so the source of the temperature of the surface of the planet is sunlight. If there were no atmosphere, then how does the amount of sunlight determine the temperature? Well, if the planet is highly reflective, then less sunlight is absorbed and goes into heating the place. If a planet is not very reflective, if it absorbs a lot of sunlight, then that light goes into making the place hotter.

This reflectivity, the ability to reflect light back to space, is often called the albedo—a-l-b-e-d-o—and it can vary. Freshly fallen snow, for example, has an albedo of maybe 70 percent, and black velvet has an albedo of a few percent, and most things fall in between. Deserts are 20 percent, and so on.

Now if the Earth had its present albedo but had no atmosphere, the average temperature of the Earth would be well below the freezing point of water. This planet would, in fact, be uninhabitable if there were no greenhouse effect. It is the greenhouse effect that brings the average temperature of the Earth well above the freezing point and permits oceans and bodies of water and all that.

So now let's say something about greenhouse effect. In a very simple way, what happens in the greenhouse effect is something like this. First of all, let me say it is a misnomer, the phrase "greenhouse effect," in that greenhouses don't work that way. But this is a historical error we needn't go into. Now consider a planet with air, like our own, which is clearly transparent—except in Los Angeles to sunlight. So visible light from the Sun comes through the atmosphere and strikes the surface and, as we were saying a moment ago, warms it up. The surface, like every other object in the universe that is not at absolute zero, radiates and at the temperatures of the surface of the Earth, it radiates mainly in the infrared part of the spectrum, radiation that is longer wave than the red part of the visible spectrum. You do not directly sense infrared radiation, sometimes called heat radiation, but it sure is there.

What happens is, a kind of equilibrium is established so that the amount of sunlight coming in from the Sun that is absorbed by the planet is precisely balanced by the amount of infrared radition emitted by the planet back to space. Now, in the case of a greenhouse effect, the visible light comes in just as it would have if there were no atmosphere, but the atmospheric gases invisible in the visible—that is, transparent in the visible part of the spectrum—tend to be opaque in the infrared part of the spectrum. The thermal radiation in the infrared is impeded from getting out. You can consider it as a kind of blanketing of the Earth in the infrared and not in the visible part of the spectrum.

As a result, the surface temperature has to go up until the radiation which is leaking out in the infrared where there isn't a lot of opacity just balances the visible radiation that is coming in. And such greenhouse effects can be very significant. In the Earth's atmosphere, the greenhouse effect is due mainly to carbon dioxide and to water vapor, with other constituents playing more minor roles, although oxides of nitrogen and other materials could be significant on a smaller scale.

Now it's not that the entire infrared spectrum is opaque. There are some parts of the infrared which are transparent, some parts which are opaque, depending on where the greenhouse gases—in this case, CO_2 and water—like to absorb. If you put more of those gases into a planetary atmosphere or into the Earth's atmosphere, you will have more opacity. You will blanket the planet more, and you will force the surface temperature to rise in order to maintain the equilibrium between what comes in and what goes out.

Now it does not follow that if you double the amount of carbon dioxide or other greenhouse gas, you double the temperature or double the opacity in a nonlinear situation. For example, you can have a region of the infrared spectrum where the CO_2 is already absorbing essentially all the infrared radiation it is going to absorb. Put in more CO_2, it doesn't change anything there. But in a different part of the spectrum, where CO_2 hasn't absorbed very much up to now, if you double the CO_2 you can cause a very significant increase in the opacity of that part of the infrared. Each of these different regions or absorption bands has to be considered in detail, separately. I stress that the problem is not a linear problem.

Now, suppose you were skeptical about the existence of a greenhouse effect or were skeptical about the possibility that it can really amount to a lot. In this case it is very useful to look at other planets because nature has arrayed for us a range of planets, some of which there is negligible greenhouse effect, others significant greenhouse effect and one a monster greenhouse effect, and it is very useful to take note of what nature has kindly provided for our edification.

So, if we look at Mars, that's a planet which has carbon dioxide in its atmosphere but the total amount of atmosphere is very little. It's something like 1 percent of the atmosphere here, and so the greenhouse effect on Mars is very small. You can accurately calculate what the average temperature of Mars ought to be from how much sunlight gets there and what its albedo is pretty well, even if you ignore the greenhouse effect.

On the other hand, let's look at our other neighbor, Venus. In the case of Venus, if you ignored the greenhouse effect you would deduce that the temperature of Venus is something like—I've got to convert from Kelvin to Centigrade—something like minus 30 or minus 40 Centigrade, when in fact the surface temperature of Venus is something like 430 Centigrade, 900 Fahrenheit, hotter than the hottest household oven. The reason for that is, we now know from spacecraft exploration—most recently the Pioneer/Venus series of spacecraft by the United States—that it is due to a massive greenhouse effect in which carbon dioxide is the principal constituent.

So, we have an example where the greenhouse effect can raise the temperature hundreds of degrees, not that anyone claims that something like Venus is in the offing, or what we do in the near future here, but it is a very useful reminder that massive changes in the planetary environment can come about from a greenhouse effect, and not just any greenhouse effect. It is precisely the same greenhouse gas we're concerned with in this hearing that is driving this enormous high temperature on the surface of Venus.

Then, in the outer solar system, Titan, the big moon of Saturn, we now know from the Voyager explorations, has a small greenhouse effect, about the same magnitude as that of the Earth, but it is not due to carbon dioxide and water vapor at all. It is due to methane, which also absorbs in the infrared but in a different part of the infrared spectrum.

So, the only lesson which I think is important to draw from this comparison with other planets is that greenhouse effects exist, that there are a variety of kinds of them, depending on the atmospheric pressure and the greenhouse gases in question. A little greenhouse gas can produce a very small temperature increment; a lot of a greenhouse gas can produce a very major temperature increment; and it is absolutely something to take into consideration and to worry about.

Now, the scientific community is in very good mutual agreement on the overall general consequences of the burning of fossil fuels, putting more carbon dioxide into the atmosphere of the Earth, producing an incremental greenhouse effect that is adding to the existing greenhouse effect. The greenhouse effect, I stress again, is a good thing. We owe our lives to it. And while differences between calculations have been stressed in the press, what is important is that all the calculations agree to the first order that doubling of the carbon dioxide in the Earth's atmosphere will increase the global temperature by a few degrees Centigrade, something of that order.

To require that scientists provide an absolutely ironclad, guaranteed value of how much the temperature will go up is probably asking too much. The calculations involve many factors, and you cannot be absolutely sure that you have included every one of them. What is striking is the unanimity of all of the calculations, so if a few degree increment in the global temperature is a bad thing then something ought to be—you ought to start worrying about what to do in that case. Also, you ought to start worrying about whether there is some way to avoid putting more carbon dioxide into the atmosphere.

These are questions of cost effectiveness. It is not a catastrophe like, for example, nuclear winter would be. It is slow, a period of many decades or a century before the effect we're talking about is fully manifested, and presumably even the worst of it is not as bad as lots of other things we could think about. But it does raise worrisome general questions. Our technology is now able to make significant changes in the environment of the planet we live in, and who would have thought that burning wood and coal to keep warm would have this quite unexpected consequence of keeping everybody warmer than they were?

When you run through the full range of consequences of modern technology, including industrial pollution, including the possible consequences of nuclear war, including the on-again, off-again concern about halocarbon propellants in spray cans, there is an overall impression, which is that we are pushing and pulling on the global environment because of innocently intended high technology, in ways that we do not fully understand and in ways that may have serious consequences. That naturally raises the question of, what institutions are there whose job it is to try to detect, identify, and if possible defuse such problems early enough.

If you look at any of these issues you find that the problems have been identified by individual scientists in the academic community, mainly who were worrying about something else and happened to stumble upon this or that effect. That got them worried and they talked to their colleagues and got other people worried. There is no institution whose job it is to systematically seek out such effects.

If we have found a half a dozen such effect in the last 20 years, let's say, it is likely, it seems to me, that there are some more that we haven't stumbled on yet, and for all we know they are more serious than any of the ones we're talking about yet, except for nuclear winter. It's hard to imagine something more serious than that. So as an issue which seems to me relevant to the purview of congressional committees such as this one, is there some institutional framework in which these problems can be systematically sought out and addressed? It seem to me an important problem.

Mr. GORE. Well, thank you very much. That's extremely helpful. Let me call first on my cochairman, Mr. Scheuer.

Mr. SCHEUER. Thank you very much, Mr. Chairman.

Thank you for your usually stimulating performance, Dr. Sagan.

Some scientists say—well, they don't use the timeframe of decades, as you did, but they use the timeframe of centuries—if this is a matter that will be having an impact on us over a period of a century or two, is it important for us to engage in a crash research program now, or is it something that we should just keep an eye cocked on over the decades and the generations, or is it something that we will, as we watch it, we will make gradual accommodations, so that when the day comes that there is a significant effect, we will have made incremental accommodations over the long period so that we will, in effect, have coped with these changes? How do we perceive it? In what kind of a timeframe do we seek comprehensive knowledge, and in what kind of a timeframe should we seek to effect some kind of remedial programs?

Dr. SAGAN. Well, certainly remedial programs depend upon having the knowledge first, and getting the knowledge is very cheap compared to the remedial programs. So it would seem to me that the course of action is very clear: Learn as much as you can about this, certainly before you do the remedial programs but so that if remedial programs are necessary, you are in a good position to do them.

Mr. SCHEUER. Can you tell us, have you scrutinized the Federal research program enough to tell us what you think of its adequacy? Are you familiar enough with it?

Dr. SAGAN. Well, I have an idea of what is happening. This is an area which is being funded at least moderately well, in my opinion. It would be interesting to ask the same question of Dr. Malone and other people who appear before you this morning but there are climate programs. The Science Foundation and NASA do support this; NOAA has some research along these lines that it supports; but I do not have the impression that the field is absolutely awash in research funds.

There, of course, are major—this issue connects with other major issues, for example, thermonuclear energy, the fusion programs, because if there were a widespread, generally available, economically sensible fusion program, that would very well replace the burning of fossil fuels in those countries which have nuclear reactors. It is important to bear in mind that the United States is not the only Nation on the planet that burns fossil fuels, so no matter what the United States does, there will be significant increments in carbon dioxide emissions from other nations. This is an example, and there are many of them, of issues that must be considered from a global perspective.

In my view, the way to deal with this problem is some large international forum in which the views of many nations can be folded in, and their economic consequences. For example—I'm only guessing—but suppose China has enormous coal reserves, and suppose that those coal reserves represent an important economic value for China. Telling China not to burn the coal because we don't want the American coastal cities to be flooded might not be received as warmly—to make a bad pun—as if there were no economic value of the burning of fossil fuels for China. These are complicated problems but they are global problems.

Mr. SCHEUER. Is UNESCO, to your knowledge, doing anything on this matter in its Man in the Biosphere program?

Dr. SAGAN. I do not know the answer to that, Congressman.

Mr. SCHEUER. Do you think it would be an appropriate subject for a global meteorological program? The question answers itself.

Dr. SAGAN. Yes.

Mr. SCHEUER. It's quintessentially global in nature.

Dr. SAGAN. It is, and I might mention that there are earth satellite initiatives that are not yet programmed, that could be very useful in monitoring global dispositions of carbon dioxide and measuring over long periods of time the various influences on the climate of the Earth, including variations in the output of the Sun, which is a significant possibility; including variations in the albedo of the Earth, place-to-place and through time. There should be, in my opinion, a systematic monitoring program of the Earth from space, which is fairly inexpensive compared to the stakes that we're talking about here, that would have excellent scientific return for its own sake, and which might provide some important hints and clues about what to do about this problem.

Mr. SCHEUER. Thank you very much, Dr. Sagan.

Thank you, Mr. Chairman.

Mr. GORE. Mr. Skeen.

Mr. SKEEN. Thank you, Mr. Chairman.

Doctor, I do want to commend you on your presentation. It was very well done and obviously you have a great command of the issue, the topic, because it always impresses me when someone can sit there and reel this business off without any notes whatever. You've given it an awful lot of thought, evidently, and I think that your reputation also portrays that kind of an image as well.

I want to ask a specific question. I have a great interest in the agricultural aspects of some of this phenomenon, and that's why I think it's great that these two committees are having joint hearings on this thing. As one who has been interested in meteorological phenomena for some time—and I have to confess that I was just a little bit surprised about El Nino, this phenomenon off of the west coast of South America and the severity with which the weather patterns have changed in the last 2 or 3 years as a result of that kind of activity. Is there any connection at all with this and the so-called CO_2 layer that we have? Has that phenomenon always been there?

Dr. SAGAN. Again, this is an issue which some of the other panelists undoubtedly know more than I do, but my understanding is that no one is suggesting that El Nino is triggered by an increase in the amount of carbon dioxide in the atmosphere. I have seen speculation that it might be triggered by volcanic explosions or that it is a periodic phenomenon in the Earth's climate, and wait long enough and it will——

Mr. SKEEN. This still underlines the importance of that kind of monitoring that we have——

Dr. SAGAN. Absolutely.

Mr. SKEEN [continuing]. And space has been a great adjunct, or the technology of space.

Dr. SAGAN. Although not as well used as it might be, but that's certainly right.

Mr. SKEEN. So your recommendation would be to expand this kind of activity to a great degree.

Dr. SAGAN. Yes, and as I was saying before, since we have many examples of international cooperation in space, a global satellite monitoring system of the Earth involving many nations——

Mr. SKEEN. Multinational.

Dr. SAGAN [continuing]. Multinational, is doable, and its symbolic significance as well as its scientific value would be high.

Mr. SKEEN. For our own preservation, it's about time we became more international with that.

Dr. SAGAN. I couldn't agree more.

Mr. SKEEN. Thank you very much, doctor. I appreciate it.

Mr. GORE. Dr. Sagan, you and a group of colleagues recently published this rather epic study, the TTAPS study on nuclear winter. We looked at that general subject in another hearing a year ago, but there is a common denominator between that subject and this one. Of course, the nuclear winter concern is so much greater and it dwarfs this issue, but there is a common denominator, and it is that our upper atmosphere seems to be far more vulnerable to disruptions of the kind that we as a civilization can create than we had previously imagined to be possible. In both instances, the discovery of the extent of that vulnerability has been serendipitous. I am wondering if you could—do you agree with that, that that's the common denominator between these two?

Dr SAGAN. Yes, and there are a bunch of other examples, both in the question of the effects of nuclear weapons—which I understand is not the purpose of this committee meeting—and in other areas. We started out, us humans, without high technology and there were only a few of us, and so no matter what we did a million years ago, we could not in a major way change the climate and environment of the planet.

Now that we are approaching 5 billion and we have very formidable technology, we are able, even accidentally, to make profound changes in the environment that supports us. It is the height of irresponsibility to make these changes and not even know that we're doing it.

Mr. GORE. Yes.

Dr. SAGAN. I mean, I would think that in a well-ordered society you would want to understand what the—you would want to make an environmental impact statement for the planet before you did any of these things. To give another example of the fragility you just mentioned, I referred a little while ago to the on-again, off-again concern about the integrity of the ozonosphere. But if you brought the ozone layer down to this room, the pressure and temperature of this room, it would be a quarter of a millimeter thick. That's all the ozone there is that's protecting us from ultraviolet light.

I mention that just as an indication of the kind of fragility we are talking about. As there get to be more people on the planet, and as our technology gets to be still more potent, we are going to be pushing and pulling the environment around in still more profound ways. There has to be some institutional, systematic means by which we try to understand what the consequences of our activities will be before we do something dreadful.

One thing I forgot to say to Mr. Scheuer's question is. in principle, one can imagine that there are irreversible changes, that you can push a thing and then it goes off on its own, and that it's a huge effort to try to pull it back. That's why it is so important to have the understanding of the phenomenon lead, the phenomenon itself. Don't make a big change until you thoroughly understand it.

So I can't emphasize strongly enough the importance of directed research on specific problems already identified, but also very broad scale research to try to understand the atmosphere/ocean/Earth system together so that we can try to identify new problems before they surprise us.

Mr. GORE. So our increased numbers and the ability of technology and industrial civilization to magnify our power to affect the world around us has put civilization on this planet in the situation of a bull in a china shop.

Dr. SAGAN. In some respects, where the bull lives only off the china, which is a poor metaphore. Right?

I mean, it's not just that the bull by ignoring things can knock stuff over. It's that the bull's very life depends on that china.

Mr. GORE. Yes, yes.

Now your studies of atmospheric systems have also given you an appreciation for something that I didn't have, and that is the fact that a change of only a few degrees in a global system can have rather dramatic consequences for the pattern of that system. Is that correct?

Dr. SAGAN. Yes, either way. A 1, 2, 3 degree lowering of the global climate—the global temperature—or a 1, 2, 3 degree raising of the global temperature, both of those can have quite serious consequences. Therefore, for example, a 1 or 2 or 3-degree decline in the global temperature doesn't sound like very much but it could destroy all wheat growing in Canada, let's say, a significant source of export food on the planet, and a few degrees increment in temperature—as the EPA and National Academy studies have stressed—raises some question about the melting of pack ice and rising of the levels of the oceans and the possible innundation of coastal cities. So a few degrees change either way can have severe global economic consequences.

Mr. GORE. OK. Now let me ask you a question based on a string of three or four assumptions. Assumption number one: a consensus emerges in the scientific community stating that not only is the greenhouse effect real, but that it will have what can fairly be described as catastrophic consequences for different regions of this country and the world, specifically, a loss of some coastal areas, including coastal urban areas; a change in the climate and ability of our grain belt to support food production at levels we are accustomed to. That's assumption number one.

Assumption number two, the scientific community arrives at a consensus stating that these effects can be largely avoided by a dramatic change in the pattern of fossil fuel use globally.

How would science communicate with public policy makers about the urgency of doing something? Would it in your view be likely that the majority would conclude in those circumstances that it was hopeless, that the political task would be overwhelming, and that our best choice would simply be to evacuate coastal areas and busily try to create new genetic strains of crops that could adapt to the new climates, et cetera, et cetera?

You see the major thrust of my question: If those assumptions fall into place, what's your view of our ability to respond to it?

Dr. SAGAN. Well, let me say first that this very important question is, in my view, not a scientific question. It is a political and economic question.

Mr. GORE. Yes.

Dr. SAGAN. I do not claim any credentials in that area. Having said that, I'll be glad to go on and try to answer your question. [Laughter]

Mr. GORE. Well, let me just interject one thought, and that is that the ability of political and economic institutions to respond to a challenge of this magnitude will depend in large part upon how clearly the challenge is perceived, which in turn will depend a great deal upon how the scientific community explains the problem, how much certainty it invests in that explanation, and how actively involved it becomes in spelling out what the clearly sensible choice might be.

Go ahead.

Dr. SAGAN. I think that the scientific issues here can be laid out clearly to lay people. I don't think there is any difficulty in doing that—however, with the caveats I said before, that is, no one knows that the effects get really serious in the year 2025 as opposed to 2085 or something of that sort. To that precision, we cannot expect that there will be consensus.

But what I despair of is, with the present global political situation, of getting the kind of international cooperation you would need here. For example, without mentioning the names of any countries, take countries which are on the cold side. Might they not think that a global warming is to their benefit? If they were to cooperate in whatever the strategy is—less burning of fossil fuels, more fusion powerplants, if and when we get them—there have to be economic motivators that the countries that are threatened will give the countries that might benefit from a global warming.

Now you also might say that the global economy is strongly interdependent, so that the enormous strains on a few nations might further disrupt the global economy, so it is in everybody's interest to cooperate here. OK, but then that requires a hitherto unprecedented degree of international cooperation on economic issues. So I think one possible consequence of what we're talking about is that the present world order is not maximized, not optimized, for responding to dangers on a global scale. Nations are concerned about themselves, not about the planet, and this kind of problem will keep coming at us as we discover more and more such potential catastrophic consequences.

Without getting into the details, the global arms race in nuclear weapons between the United States and the Soviet Union has just this character of being concerned only about the United States and the Soviet Union, and neither nation taking much concern at all about other nations far from their dispute—the dispute of the United States and the Soviet Union—other nations that we now recognize have everything at stake in case of nuclear war.

Mr. GORE. Well, very good.

Do you have any questions?

Mr. REID. No.

Mr. SKEEN. No.

Mr. GORE. Well, I want to thank you for—did you have a question?

Mr. SCHEUER. Just one observation, sort of illuminating a remark you made about one man's feast is another man's famine. I understand that this warming effect that would inundate most of our coastal cities would have the effect in Russia of making Russia one of the major wheat-growing areas of the world. It would have, had she been in that condition now, it would have entirely eliminated her dependence on Canada, Australia, and the United States for wheat. It would be very much to Russia's interest.

So you have a perfect example there of the fact that Russia would benefit enormously from a 2- or 3-degrees increase in her temperature.

Dr. SAGAN. On the other hand, there's not very much that the Soviet Union could do about this. I mean, commands to various distant oblasts to burn more fuel is not going to hurry up this procedure. We have to recall what the time scale of these changes is.

Mr. SCHEUER. Yes, but the urgency of her cooperation in remedial programs might be somewhat diminished by the fact that she would be benefited by this phenomenon.

Dr. SAGAN. It might be, except that when we then add four or five or six or seven or eight other kinds of global problems, you will find some which go the other way, in which the United States would differentially benefit and not the Soviet Union. If you just step back from the planet and look down at it, it is clearly in the interest of everybody on the planet to cooperate on these issues.

Mr. SCHEUER. Thank you, Mr. Chairman.

Mr. SKEEN. Mr. Chairman?

Mr. GORE. Yes.

Mr. SKEEN. By the same token, if that happened, the Russians' so-called winter syndrome in their attitude might be changed a little bit. They would be a little happier people than they are. [Laughter.]

Dr. SAGAN. And you think Americans would, by the same token, get much more grumpy?

Mr. SKEEN. Well, no. It's hard for us to get any grumpier or become more critical. [Laughter.]

Mr. GORE. Well, great. I really thank you for giving us this overview from a fresh perspective to start off this hearing. It is extremely helpful and, again, I want to thank you for taking the time to delve into this. We are very grateful. We have worked with you in the past, and we look forward to working with you in the future. As you know, I admire the work that you do, Dr. Sagan. Thank you again for getting us off to a good start today.

Dr. SAGAN. Thank you very much, Mr. Chairman.

Mr. GORE. Let me call our first panel of witnesses: Dr. John Trabalka, with the Environmental Sciences Division at Oak Ridge National Laboratories; Dr. Wallace Broecker from the Geochemistry Department at Lamont-Doherty Observatory in Palisades, NY; and Dr. William Jenkins from the Woods Hole Oceanographic Institution in Woods Hole, MA.

Dr. Broecker, I am sorry I mispronounced your name earlier. Did I get it right that time?

Mr. BROECKER. That's right.

Mr. GORE. OK. All right. Thank you.

We will hold off on questions until all three panelists have completed their statements. We would like to begin with Dr. John Trabalka from the Environmental Sciences Division at Oak Ridge National Laboratories.

Dr. Trabalka, welcome to you. We are delighted to see you, and please proceed.

STATEMENT OF DR. JOHN TRABALKA, ENVIRONMENTAL SCIENCES DIVISION, OAK RIDGE NATIONAL LABORATORIES

Mr. TRABALKA. Thank you, Mr. Gore. I first would like to thank the joint committees for the invitation to testify, and I also request that I be allowed to submit a copy of my written testimony and my vitae for the proceeding record.

Mr. GORE. Without objection, we'll do that.

Mr. TRABALKA. My name is John R. Trabalka. I am manager of the Global Carbon Cycle Program in the Environmental Sciences Division at Oak Ridge National Laboratory. The ORNL Program is a major component in the U.S. Department of Energy's carbon cycle research program.

The DOE Carbon Cycle Research Program is directed toward improving the quantitative basis for understanding the global carbon cycle to more accurately predict future levels of atmospheric carbon dioxide. The research goals and needs are described in the latest Carbon Cycle Research Program plan published by the U.S. Department of Energy. It carries a December 1983 date.

The principal purpose of the ORNL Program is to provide assistance to the Division of Carbon Dioxide Research in development, management, and in-house research activities for the DOE Carbon Cycle Research Program. Oak Ridge National Laboratory has played a role in carbon cycle research for over two decades. The laboratory's role in research management for the DOE has a more recent origin in fiscal year 1982.

In carrying out tasks assigned by DOE, the program is responsible for monitoring carbon cycle research progress, identifying research needs, and recommending methods for fulfilling these needs. The ORNL Program management staff now executes and administers subcontracts to universities and major research institutions for research to fulfill many of these needs outlined in the current research plan.

In fisal year 1983 the ORNL Program was directed to concentrate on global carbon cycle model development and terrestrial biospheric data acquisition. The ORNL Program management staff also prepares technical and topical reports. Major activity underway involves the coordination and integration of efforts from DOE contractors and the international CO_2 research community for a 1985 state-of-the-art report on the global carbon cycle. We expect the 1985 state-of-the-art report to provide another source of information on research needs and for further definition and refinement of certain key program areas, including a Core Ocean Measurements Program.

The principal technical objective of the DOE Global Carbon Cycle Program at ORNL is to develop a quantitative basis for understanding the global biogeochemical cycle of carbon by balancing the reservoirs and fluxes in the global cycle and implementing simulation models to describe the dynamic behavior of the global carbon cycle and its components. Another objective of this research is to further the scientific methodology for accurate projection of future CO_2 levels in the atmosphere.

Mathematical models of the carbon cycle are needed to address these questions, and are being developed and updated with refinements in basic understanding and improved estimates of key parameters. A mathematical model developed by the DOE Program at ORNL is being used to make CO_2 projections for the forthcoming state-of-the-art report on the global carbon cycle. Sensitivity and error analyses provide a basis for selecting aspects of models and data bases that require refinement, and basic data sets in key areas underlying carbon cycle models are being refined and augmented where indicated.

As a direct consequence of our programmatic assignment by DOE, particular attention in both the intramural and extramural research projects during the past fiscal year was devoted to improving our understanding of the terrestrial component of the cycle. The key unresolved issues in the Carbon Cycle Research Program appear to in lve disparate estimates of CO_2 releases by the land biosphere anu of CO_2 uptake by the ocean.

Over the past two millenia, terrestrial ecosystems, particularly the forests, have been a source of CO_2 to the atmosphere many times larger than that from fossil fuels. These CO_2 releases occurred principally as a result of forest clearing during agricultural expansion an timber harvesting. Such changes in land use result in losses of carbon formerly stored above ground in wood and below ground in soil and roots. During the past two millenia, half of the living terrestrial biosphere was eliminated by human influence.

The principal controversy involves the magnitude and timing of the CO_2 loss from the land and the rate of CO_2 uptake by the oceans over the past 200 years. This was a period when human population was increasing exponentially and significant exploitation of the land resources of the Western Hemisphere and tropical forests throughout the world occurred. Significant population growth in the tropics and associated exploitation of these forests are still occurring and are projected to continue for several decades.

Around 1980, published estimates of the rate of carbon uptake by the oceans were too low to accommodate even moderate estimates of CO_2 releases from vegetation and soils. Uncertainty about the history of atmospheric CO_2 concentrations over the past 200 years made reconciling the disparate estimates of terrestrial releases and the ocean uptake difficult.

Progress has defined a technical basis for resolution of the issues and for convergence of the terrestrial release and ocean uptake estimates. New evidence that the atmospheric CO_2 concentration may have been as low as, say, 260 parts per million in the year 1800, means that there has had to have been a substantial nonfossil source of CO_2 to the atmosphere—for example, from vegetation and soil—over the past 200 years. The total amount contributed by the land biosphere could have been as much as that contributed by fossil fuels.

These findings suggest that the oceans may be assimilating more CO_2 from the atmosphere than has heretofore been estimated. Improvements in globally averaged carbon cycle models produced by the ORNL Program have resulted in new estimates of CO_2 uptake by the oceans which are higher than earlier estimates on the order of 25 percent. However, these current ocean models are still able to accommodate a significant CO_2 release from terrestrial ecosystems only if the bulk of the release occurred in the previous century and then declined radically to the present, or if the average level of release was much lower than some historical reconstructions indicated.

Both requirements are still in conflict with results from relatively recent reconstructions of historical CO_2 releases from the land biosphere. However, considerable evidence produced over the past year from research supported by the ORNL global carbon cycle program supports a significant overall lowering of the magnitude of the historical terrestrial carbon flux.

However. one of the chief remaining sources of uncertainty for both past and present estimates of terrestrial carbon release is the lack of adequate documentation for past patterns of land use. In the next stage of research, emphasis needs to be placed on geographically based analyses of land use change, using high-spatial-resolution models differentiated by ecosystem types and disturbance categories. These more sophisticated models of the land biosphere will also have the capability to respond to projected climate changes and eventually to CO_2 fertilization responses.

The activities of documenting the patterns of changes in land areas over time and developing the new terrestrial models required for data analysis are being closely coordinated. Particularly important are data on forest clearing and other land use changes being assembled by forest historians from Duke University. Pilot studies devoted to potential applications of remote sensing via satellite imagery to document and confirm present-day land use patterns and to monitor future changes are underway at the Ecosystems Center, Marine Biological Laboratory at Woods Hole. Once fully developed, the use of satellite imagery could provide a most accurate method for determining land use change and estimating the resulting carbon fluxes. The attached photographs that I have provided you suggest the significant potential for this technology in both defining the location and extent of major ecosystems and for defining the rates at which man is changing the face of the landscape.

One promising alternative approach to resolving the controversy related to terrestrial CO_2 releases and ocean uptake appeared to make use of the carbon isotope record for atmospheric CO_2 contained in tree rings. The scientific issues associated with interpretation of C13 records in tree rings involves the separation of the isotopic noise caused by tree physiology, local environmental conditions, climate effects, and CO_2 fertilization responses. However, the latest results reinforce our concerns about the potential variability of the tree ring record and confirm that basic research on the physiological mechanisms which control isotope fractionation in trees will be a necessary precursor to further use of tree ring data in carbon cycle research.

Further improvements in ocean models for analysis of the carbon cycle/climate issue are also critically needed. This effort will require development and testing of more physically realistic representations; multidimensional models of ocean circulation and carbon transport. There currently is not an adequate data base with which to construct and properly calibrate such models on a global scale.

A Core Oceanic Measurements Program is needed, therefore, to support the further development of oceanic carbon cycle/climate models. Measurements of CO_2 concentrations in surface water are needed in combination with gas exchange data to calculate the flux of CO_2 between the atmosphere and the ocean. Repeated measurements of dissolved CO_2 in surface water at key locations and of total inorganic carbon as a function of depth at carefully selected stations over the globe should provide a long-term record of CO_2 uptake by the ocean. These data are urgently needed to develop secular trends of carbon buildup in the ocean comparable to those observed in the atmosphere.

Tracer data are also used to describe ocean mixing and transport of carbon to the deep oceans. Oceanographic research programs have collected important tracer data at a number of key locations. However, the sparseness of temporal coverage and geographic coverage in the upper layers of the ocean currently limits analyses of the oceanic carbon cycle. Successive sampling programs over a period of decades appear to be needed to clarify the nature of mixing and exchange in order to develop a truly global model of ocean circulation and uptake. This requires that we adequately analyze and interpret the existing data, and the data successively produced by each set of regional ocean measurements, in planning future measurements programs in order to make the most efficient use of available resources.

The resolution of the technical issue involving disparate estimates of historical terrestrial releases in ocean uptake is needed if we are to place confidence in projections of future atmospheric CO_2 levels with global carbon cycle models and to understand how the biogeochemical system operates. Simply put, if we cannot balance the carbon cycle for the present, how can we expect to make accurate predictions of the future?

However, resolution of this issue will also allow us to define the time series, that is, the history of atmospheric CO_2 concentrations as far back in time as our terrestrial release reconstructions can be made. This will provide another means for checking and placing limits on the values of the preindustrial atmospheric CO_2 levels. The climatic implications associated with defining the so-called preindustrial level of atmospheric CO_2 will be described in later testimony. Thus, information provided by the carbon cycle research program will be important in helping to check the predicted climatic responses from climate models against actual observations of climate behavior.

Since it is not possible to cover all research activities and associated needs in one set of testimony, I have attempted to highlight what are believed to be the most critical issues and ask that you refer to the carbon cycle research program plan and to my testimony, my written testimony, as a source of additional information.

I believe I will close there with my statement.

[The prepared statement of Dr. Trabalka follows:]

TESTIMONY PRESENTED TO

SUBCOMMITTEE ON NATURAL RESOURCES, AGRICULTURE RESEARCH AND ENVIRONMENT AND SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT OF THE SCIENCE AND TECHNOLOGY COMMITTEE

U. S. HOUSE OF REPRESENTATIVES

February 28, 1984

Joint Hearing on Carbon Dioxide and the Greenhouse Effect

DR. JOHN R. TRABALKA

Manager, Global Carbon Cycle Program

Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

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I. INTRODUCTION

A. Personal Qualifications

My name is John R. Trabalka. I am Manager of the Global Carbon Cycle Program in the Environmental Sciences Division of the Oak Ridge National Laboratory (ORNL). The ORNL program is a major component in the U.S. Department of Energy (DOE) Carbon Cycle Research Program. I can assure you that the following scientific judgments and opinions reflect those of a substantial portion of my professional peers. I am a scientist who has been personally involved in research on the broad topic of biogeochemical cycling and effects of pollutants since 1971. Most recently, I have been involved with research on sensitivity/uncertainty analyses of global carbon cycle models, and projections of future atmospheric carbon dioxide (CO_2) levels with such models. I also was an organizer, cochairman, and am now chief editor of the proceedings, for a recent international symposium on the technical issues associated with the global carbon cycle. I served for two years as the Deputy Manager of the ORNL program before assuming my present role. I am currently responsible for the research management of a multidisciplinary group of over 30 scientists working in this field at Oak Ridge National Laboratory and at other centers of excellence at universities and research laboratories.

B. Carbon Cycle Research Program

The DOE Carbon Cycle Research Program is directed toward improving the quantitative basis for understanding the global carbon cycle to more accurately predict future levels of atmospheric carbon dioxide. There are several central issues. Anthropogenic emissions result in a shift in the global carbon equilibrium. Accurate future atmospheric CO_2 predictions, therefore, are needed because increased atmospheric levels will persist for some centuries even if fuel use is abated. Therefore, it is necessary to determine long-term trends (and forms thereof) of fossil fuel use, atmospheric CO_2 levels, and sizes of the biospheric and oceanic carbon reservoirs. Dynamic global carbon models are necessary to predict future atmospheric CO_2 concentrations. Most important for development of accurate models is a quantitative understanding of the complex set of fluxes (exchanges) of carbon among the reservoirs (see Figures). Additional exchanges of CO_2 will be evaluated to ensure that important fluxes in the global cycle have not been overlooked. The time-dependent balance between the fluxes determines the rate at which CO_2 builds up in the atmosphere. Historical values of atmospheric CO_2 need to be obtained as benchmarks, because these values will affect conclusions about the oceans' and the biosphere's capacity to withdraw airborne CO_2. The research goals and needs are described in the latest Carbon Cycle Research Program Plan published by the U.S. Department of Energy (December 1983).

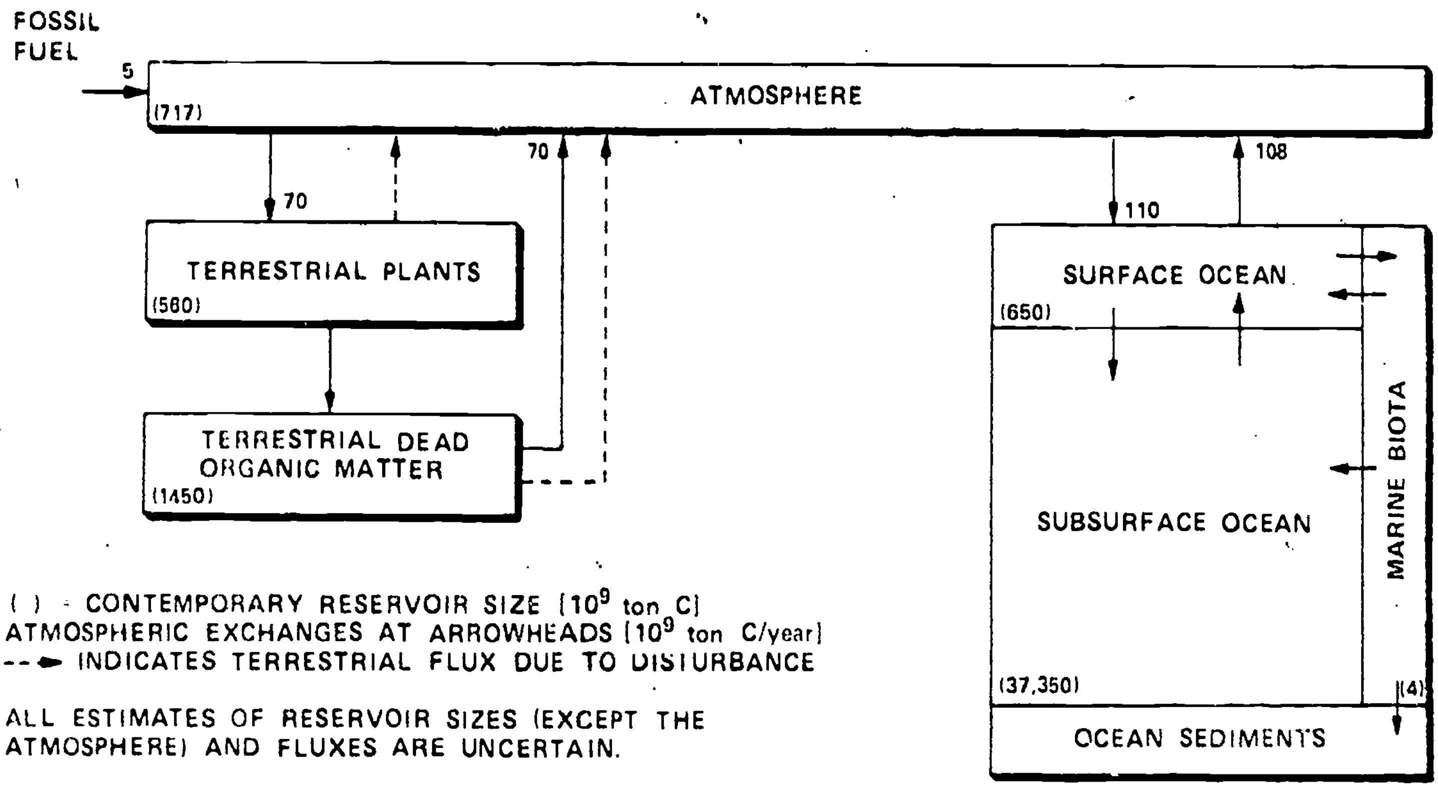
C. Oak Ridge National Laboratory Global Carbon Cycle Program

The principal purpose of the Oak Ridge National Laboratory's (ORNL) Global Carbon Cycle Program is to provide assistance to the Division of Carbon Dioxide Research in development, management, and research activities for the DOE Carbon Cycle Research Program. Oak Ridge National Laboratory has played a major role in carbon cycle research for over two decades. The Laboratory's role in research management for the DOE has a more recent origin in fiscal year 1982. In carrying out the tasks assigned by DOE, the program is responsible for monitoring carbon cycle research progress (ORNL subcontracts to other research institutions, in-house projects, and Department of Energy grants), identifying research needs to support global carbon cycle model development and recommending methods for fulfilling these needs. The latest Carbon Cycle Research Program Plan was developed through a lengthy series of peer reviews by the scientific community and revisions. It is believed to represent the current consensus of knowledgeable experts.

The ORNL program management staff now executes and administers subcontracts to universities and major research institutions for new or

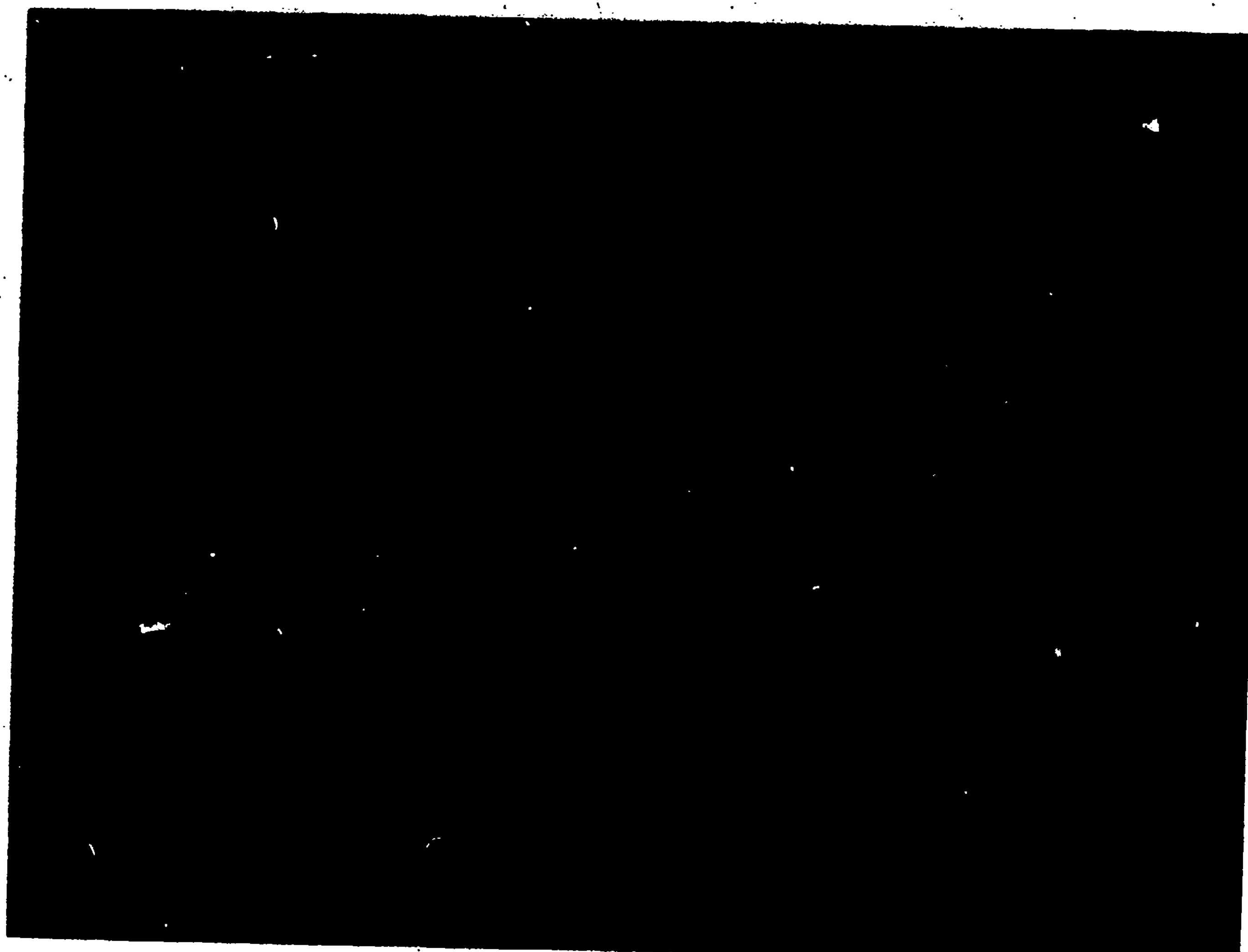
CARBON INVENTORY: EXCHANGE OF PRINCIPAL RESERVOIRS

ORNL DWG 81 20009R3



( ) - CONTEMPORARY RESERVOIR SIZE [10^9 ton C]
ATMOSPHERIC EXCHANGES AT ARROWHEADS [10^9 ton C/year]
--➔ INDICATES TERRESTRIAL FLUX DUE TO DISTURBANCE

ALL ESTIMATES OF RESERVOIR SIZES (EXCEPT THE ATMOSPHERE) AND FLUXES ARE UNCERTAIN.



continuing research supporting many of the areas outlined in the latest Carbon Cycle Research Plan. In fiscal year 1983, the ORNL program was directed to concentrate on global carbon model development (including terrestrial and oceanic subcomponents), and terrestrial biospheric data acquisition.

The ORNL program management staff also prepares technical and topical reports to update research progress, to provide responses to specific questions, and to resolve technical issues. A major activity under way in this area involves the coordination and integration of contributions from DOE contractors and the international CO_2 research community for a 1985 State-of-the-Art (SOA) Report for DOE on the global carbon cycle.

In support of the State-of-the-Art Report, ORNL organized and hosted the Sixth ORNL Life Sciences Symposium on the topic: The Global Carbon Cycle: Analysis of the Natural Cycle and Implications of Anthropogenic Alterations for the Next Century, in Knoxville, Tennessee, on October 31 - November 2, 1983. The symposium was sponsored jointly by federal agencies and industry: the Department of Energy; National Science Foundation; Electric Power Research Institute; National Oceanic and Atmospheric Administration; and the Gas Research Institute. The symposium was attended by 180 scientists representing 10 countries. The symposium was organized to examine the scientific basis for extrapolating present knowledge about fluxes, sources, and sinks in the global carbon cycle to predict changes in atmospheric CO_2 concentrations resulting from anthropogenic influences. The published proceedings, containing invited contributions by internationally recognized scientists, will provide a major resource of current technical information to both scientists and decision makers.

The recent symposium on the global carbon cycle and the SOA Report, which will draw on the talents of the international community for authors and reviewers, are examples of a developing international outreach through the DOE Global Carbon Cycle Program at ORNL. Several program scientists are currently located at key research centers in Europe, another will participate in an ocean measurements project supported by the French government, and still others have established needed contacts and research efforts throughout the tropical regions of the developing world. Other international researchers involved in the program (e.g., at the University of Bern, Switzerland) are directly supported by the DOE. An international issue such as the CO_2-climate problem requires international participation.

II. TECHNICAL OBJECTIVES

The principal technical objective of the DOE Global Carbon Cycle Program at ORNL is to develop a quantitative basis for understanding the global biogeochemical cycle of carbon, i.e., by "balancing" the reservoirs and fluxes in the global carbon cycle, and implementing simulation models to describe the dynamic behavior of the global carbon cycle and its components. Another objective of this research is to further the scientific methodology for assessing the response of the global carbon cycle, particularly changes in atmospheric CO_2 concentration, to further releases of CO_2 by fossil-fuel combustion; i.e., so that accurate projections of future CO_2 levels in the atmosphere can be made. How much of the observed atmospheric CO_2 increase is attributable to fossil fuels? How much is due to other sources? Would the increase have been greater, less, or essentially the same without the response of the terrestrial biosphere? How rapid will the atmospheric CO_2 increase be in the future? Mathematical models of the carbon cycle are needed to address these questions, and are being developed and updated with refinements in basic understanding and improved estimates of key parameters. A mathematical model developed by the DOE program at ORNL is being used to make CO_2 projections for the forthcoming SOA report on the global carbon cycle. Sensitivity and error analyses provide a basis for selecting aspects of models and data bases that require refinement. Basic data sets in key areas underlying carbon-cycle models are being refined and augmented where indicated.

III. ONGOING RESEARCH ACTIVITIES AND FUTURE NEEDS

A. Key Unresolved Issues

As a direct consequence of our programmatic assignment by DOE, particular attention in both the intramural and extramural research projects during the past fiscal year was devoted to improving our understanding of the terrestrial component of the cycle. The key unresolved technical issues in the carbon cycle research program involve disparate estimates of CO_2 releases by the land biosphere and of CO_2 uptake by the oceans. Resolution of these issues will make the greatest contributions to the overall objective of "balancing the carbon cycle." The balance between the terrestrial source and the ocean sink for CO_2 is one of the two key determinants for the rate at which fossil fuel CO_2 builds up in the atmosphere. The other is the rate of fossil fuel emissions. If the oceans are currently absorbing a significant amount of terrestrial CO_2, the future rate of the atmospheric CO_2 increase could be significantly slower than expected.

Over the past two millenia, terrestrial ecosystems, particularly the forests, have been a source of CO_2 to the atmosphere many times larger than that from fossil fuels. These CO_2 releases occurred principally as a result of forest clearing during agricultural expansion and timber harvesting. Such changes in land use result in losses of carbon formerly stored above-ground in wood and below-ground in soil and roots (as they decay). During the past two millenia, half of the living terrestrial biosphere was eliminated by human influences. The principal controversy involves the magnitude and timing of the CO_2 loss from the land and the rate of CO_2 uptake by the oceans over the past 200 years. This was a period when human population was increasing exponentially, and significant exploitation of the land resources of the Western Hemisphere, and tropical forests throughout the world, occurred. Significant population growth in the tropics and associated exploitation of the forests are still occurring, and are projected to continue for at least several decades. Circa 1980, published estimates of the rate of carbon uptake by the oceans were too low to accommodate even moderate estimates of CO_2 releases from vegetation and soils over the past 200 years. Uncertainty about the history of the atmospheric CO_2 concentration over that same period made reconciling the disparate estimates of terrestrial releases and ocean uptake difficult.

B. Recent Technical Progress

Progress in several key areas in just the past year have defined a technical basis for resolution of the issues, and for more substantial convergence of the terrestrial release and ocean uptake estimates over the next decade. New evidence that the atmospheric CO_2 concentration may have been as low as 260 ppmv in the year 1800, described to you in detail in earlier testimony by the representative of the DOE, means that there has to have been a substantial non-fossil source of CO_2 to the atmosphere, e.g., from vegetation and soil, over the past 200 years. The total amount released from the land biosphere could have been as large as the contribution from fossil fuels.

These new findings suggest that the oceans may be assimilating more CO_2 from the atmosphere than has heretofore been estimated. Improvements in globally averaged ocean carbon cycle models produced by the ORNL Global Carbon Cycle Program (Peng and Broecker; research jointly supported with the National Science Foundation, in preparation) have resulted in new estimates of CO_2 uptake by the oceans which are higher than earlier estimates by 25%. However, these current ocean models are still able to accommodate a significant CO_2 release from terrestrial ecosystems only if the bulk of the release occurred in the previous century and then declined to the present, or if the average level of release was much lower than some historical reconstructions indicated. Both requirements are still in conflict with results from relatively recent reconstructions of historical CO_2 releases from the land biosphere. However, considerable evidence produced over the past year from research supported by the ORNL Global Carbon Cycle Program now supports a significant overall lowering of the magnitude of the historical terrestrial carbon flux produced by human activities.

One principal finding from two recent efforts (one at Duke University - Schlesinger in press; the other in-house - Mann submitted) devoted to analyses of data on soil carbon behavior following cultivation is that the amount lost may only be one-half the value in models most recently used by researchers on the terrestrial carbon cycle. Another finding has been that in many cases carbon rebounds in tropical soils under pasture to levels approaching those of the original forest (research by the University of Illinois and the University of Puerto Rico - reported in Auerbach and Reichle in press). Current models assume a permanent reduction in soil carbon when tropical forests are converted to grazing land. These models were exercised to produce the higher estimates of past carbon releases from the land biosphere. Since soils contain nearly three-fourths of the terrestrial carbon pool, a reduced loss of soil carbon, such as that indicated by the new results, should result in a significant lowering of estimates of terrestrial carbon releases on this basis alone.

Another major finding was that the mass of the total carbon pool in tropical forest vegetation may be 50% less than previous estimates (Brown and Lugo in press) used by the scientific community in attempts to model the terrestrial cycle. The significant implication is that much less CO_2 would be produced when tropical forests are cleared, thus reducing the terrestrial source of atmospheric CO_2 from the tropics. This should result in a significantly lowered estimate, in particular, for the period covering the past 30 to 40 years in which the disparate estimates of terrestrial fluxes and ocean uptake are most difficult to balance.

However, one of the chief remaining sources of uncertainty for both past and present estimates of terrestrial carbon release is the lack of adequate documentation for past patterns of land use. In the next stage of research, emphasis needs to be placed on geographically based analyses of land-use change (see attached Map of Major World Ecosystem Complexes) using a high-spatial-resolution model differentiated by ecosystem types and disturbance categories. These more sophisticated models of the land biosphere will also have the capability to respond to projected climate changes, and, eventually, to CO_2 fertilization responses. Under the support of DOE, and with some limited involvement from other federal agencies, investigators are assembling more detailed data on the history of land use at regional levels required for improved terrestrial carbon cycle models now under development. These two activities of documenting the patterns of changes in land areas over time and developing the new terrestrial models required for data analysis are being closely coordinated. Particularly important are data on forest clearing and other land-use changes being assembled by forest historians from Duke University. Pilot studies devoted to potential applications of remote sensing via satellite imagery to document and confirm present-day land-use patterns and to monitor future changes are underway at the Ecosystems Center, Marine Biological Laboratory, at Woods Hole, Massachusetts. Once fully developed, the use of satellite imagery could provide a most accurate method for determining land-use change and estimating the resulting carbon fluxes (see Figures). It is expected that refinement of our estimates of both past and present carbon releases from the land biosphere via new modeling and data assembly activities will realistically require a decade or more of concerted effort to accomplish.

One promising alternative approach to resolving the controversy related to terrestrial CO_2 releases and ocean CO_2 uptake appeared to make use of the carbon isotope record for atmospheric CO_2 history contained in tree rings. The scientific issue associated with interpretation of ^{13}C records in tree rings involves the separation of the isotopic noise caused by tree physiology, local environmental conditions, climatic effects, and CO_2 fertilization responses. New research results are available from the ORNL university subcontracts for trees from Pacific Coast sites (University of Washington) and the southwestern United States (University of Arizona). State-of-the-art corrections were made for some of these extrinsic factors which produced strikingly different results when compared to those from earlier tree ring studies which did not take these phenomena into account. The new records indicate a much slower rate of change in the CO_2 content of

Figure is a NOAA-7 AVHRR satellite image of the African continent made in 1982. Provided by C. J. Tucker et al., NASA/Goddard Space Flight Center, Greenbelt, Maryland. Compare the ecosystem distributions indicated by differences in colors with the patterns on the Map of World Ecosystem Complexes.

Red - Tropical rain forest
Green - Seasonal forest and grassland
Blue - Savanna
Purple - Wooded steppe
Yellow - Desert and semidesert
Turquoise - Irrigated agriculture
Light Blue - Water

ORNL-DWG 84-7787

LAND-COVER CLASSIFICATION OF AFRICA PRODUCED FROM SATELLITE IMAGERY

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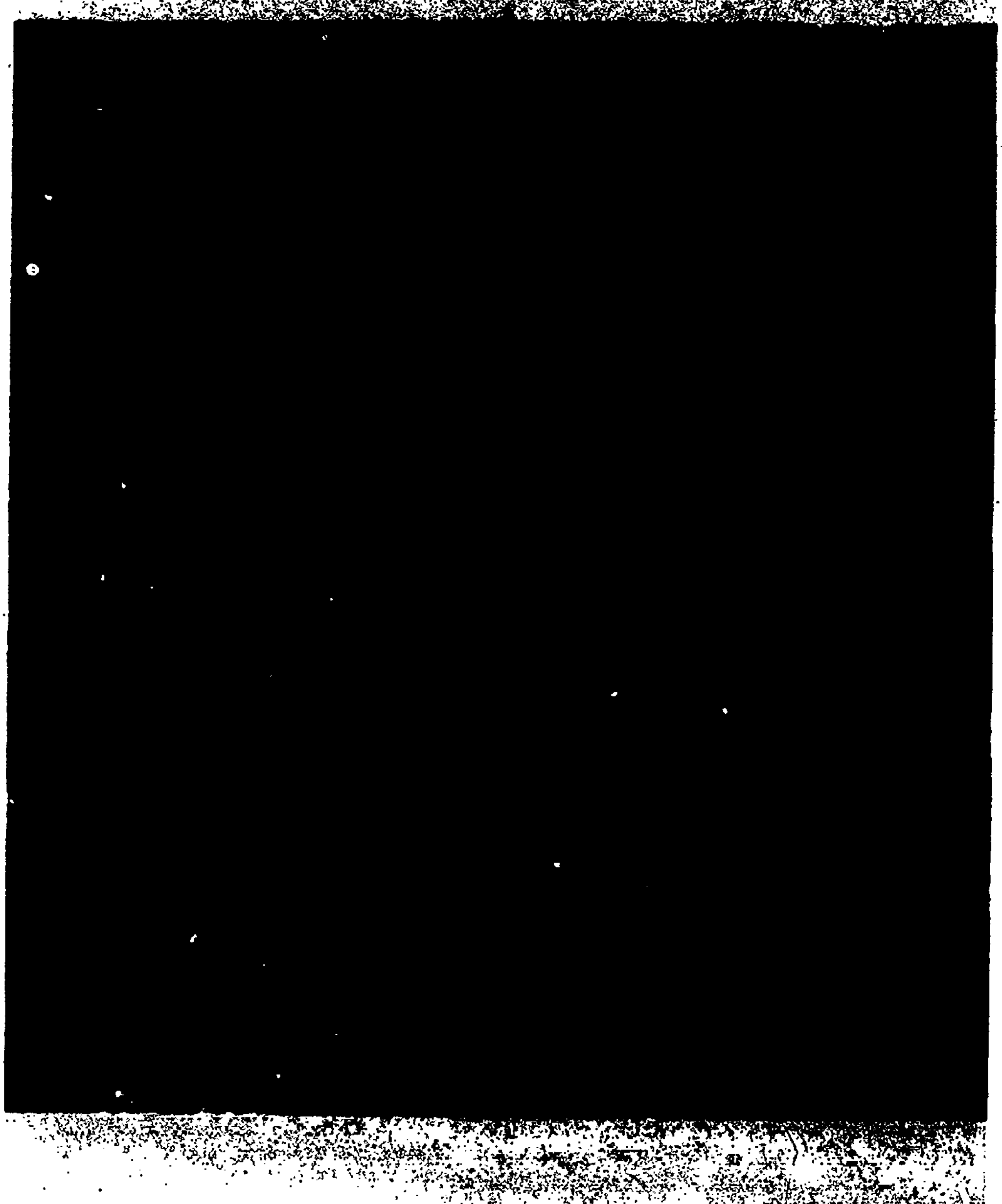
Figure is a 30 km x 30 km section of a 1981 Landsat scene from Brazil. Dark red areas are undisturbed tropical moist forest. Light pink, white, and light blue areas are, respectively, regrowing vegetation in cleared areas, cleared areas, and bare soil. The parallel roads are about 5 km apart. All the visible clearing has occurred since 1973 and the majority has occurred since 1978. At this rate complete clearing could occur within another decade. Provided by G. M. Woodwell et al., The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts.

FIGURE 3(c)



the atmosphere, and, correspondingly, a much lower rate and total amount of historical carbon input from the terrestrial biosphere, particularly over the past 30 to 40 years. Estimates of the preindustrial atmospheric CO_2 level from the uncorrected and corrected tree ring data now bracket the preindustrial CO_2 level estimated from other sources. However, the new results also reinforce concerns about the potential variability of the tree ring ^{13}C record and confirm that basic research on the physiological mechanisms which control isotope fractionation in trees in order to reduce the residual variations will be a necessary precursor to further use of tree ring data in carbon cycle research. Because tree ring records contain potentially important information on past climates and on CO_2 fertilization of the biosphere in addition to carbon cycle processes, a high priority will be placed on restructuring tree ring research to focus on critical physiological questions identified by the ongoing research program.

Further improvements in ocean models for analysis of the carbon cycle/climate issue are critically needed. This effort will require development and testing of more physically realistic representations; multidimensional, i.e., resolved by latitude and depth or by latitude, longitude, and depth, models of oceanic circulation and carbon transport. There currently is not an adequate data base with which to construct and properly calibrate such models on a global scale. Results from attempts to apply such models to the North Atlantic Ocean, a region in which the most detailed oceanic data are available, have thus far been equivocal. On the one hand, simulation of the time-dependent ocean depth penetration of the radioisotope tracer tritium produced from weapons tests with a three-dimensional model produced quite different results from those of simpler models (Sarmiento 1983), and seems to offer the promise that significant changes in estimates of ocean uptake may yet be possible. However, comparisons among two-dimensional carbon cycle models for the North Atlantic Ocean thermocline, calibrated by multiple tracers (^{3}H, ^{3}He, bomb ^{14}C, ^{85}Kr, and Freons), did not produce the hoped-for increases in CO_2 uptake - model to model differences in uptake were quite small (Peng and Broecker in preparation).

A final conclusion is not possible at this time and will not be obtained until a global ocean model is developed and properly calibrated. These preliminary results are a signal that a more physically realistic model of ocean circulation may not necessarily represent a larger oceanic sink for CO_2 uptake, and that a balanced approach to overall research on the carbon cycle is necessary. Only painstaking research and careful monitoring of the movements and distribution patterns of oceanic tracers and of changes in oceanic carbonate chemistry over several decades appear to provide the important information needed for ocean modeling. However, research on other important components of the program should not be sacrificed to support research on the oceanic component.

A core oceanic measurements program is needed, therefore, to support the further development of oceanic carbon cycle/climate models. Measurements of the dissolved free-CO_2 (pCO_2) concentrations in surface seawater are needed in combination with gas exchange data to calculate the flux of CO_2 between the atmosphere and the ocean. These measurements must be integrated from data collected from a large number of carefully selected stations over the global ocean and on a seasonal basis in order to provide an accurate picture of global CO_2 uptake by the ocean. Repeated measurements of pCO_2 at key surface locations and of total inorganic carbon (ΣC) as a function of depth at carefully selected stations over the globe should provide a long-term record of CO_2 uptake by the ocean. These data are urgently needed to develop secular trends of carbon buildup in the ocean comparable to those observed in the atmosphere. This information will be used to verify and refine the models of the global carbon cycle which, in turn, will be used to project future levels of atmospheric CO_2. The ΣC measurements in the deep waters of the ocean also provide a method for estimating preindustrial atmospheric CO_2 concentrations. Differences between dissolved inorganic carbon concentrations and alkalinity over time should provide information on changes in dissolution or precipitation of sedimentary calcium carbonate. If significant calcium carbonate dissolution occurs (with a resulting increase in alkalinity of seawater), the ocean's capacity for CO_2 uptake would be enhanced, and the buildup of atmospheric CO_2 might proceed at a slower rate than we might now project.

Tracer data [total carbon, certain radioisotopes (^{14}C, ^{3}H, ^{3}He, ^{85}Kr, ^{39}Ar), and Freons] are also used to desc'ibe ocean mixing and transport of carbon to the deep ocean. Oceanographic research programs, such as GEOSECS and TTO, have collected important tracer data at a number of key stations. However, the sparseness of temporal and geographic coverage in the upper layers of the ocean and the imprecision of some data sets currently limit definitive analyses of the oceanic carbon cycle. Additional analyses and successive sampling programs over a period of decades appear to be needed to clarify the nature of mixing and exchange in each region in order to develop a truly global model of ocean circulation and carbon uptake. This requires that we adequately analyze and interpret the existing data, and the data successively produced by each set of regional ocean measurements, in planning future measurements programs in order to make the most efficient use of available resources.

The results of this data collection, assembly, and analysis effort are the primary basis for development of the multidimensional ocean models described earlier. Thus, oceanic carbon and other chemical tracer measurements are made in order to characterize oceanic processes which control CO_2 uptake, to provide numerical data used in developing, refining, and testing mathematical models of the global carbon cycle, and to monitor long-term changes in the global carbon system produced by increasing atmospheric CO_2. Measurable changes in oceanic carbon chemistry are particularly important as a continuing check on the accuracy of parameters and concepts used in our models. Much is yet unknown about the role of the oceans in the carbon-climate system, and, in Peter Brewer's words, "We should not be too complacent. Nature has vast resources with which to fool us; the last glaciation was apparently accompanied by massive CO_2 transfers to and from the ocean, the causes, consequences, and explanations of which are poorly understood today" (Brewer 1983).

In summary, significant progress is being made toward resolution of the major scientific issues associated with the global carbon cycle. However, both the complexity of the issues and the nature of the research needed for resolution currently indicate that a long-term effort over several decades is needed.

C. Resolution of Biosphere/Ocean Confict-Impact on CO_2 and Climate Modeling

The resolution of the technical issue involving disparate estimates of historical terrestrial releases and ocean uptake is obviously needed if we are to place reasonable confidence in projections of future atmospheric CO_2 levels with global carbon cycle models and to understand how the biogeochemical system operates. Simply put, if we can not balance the carbon cycle for the present, how can we expect to make accurate predictions of the future?

However, resolution of this issue will also allow us to define the time-series, i.e., the history, of atmospheric CO_2 concentrations as far back as our terrestrial release reconstructions can be made. This will provide another means for checking and placing limits on the values of the preindustrial atmospheric CO_2 levels. The climatic implications associated with defining this so-called preindustrial level of atmospheric CO_2 have been described in testimony presented earlier by the representative of the DOE. Thus, information provided by the carbon cycle research program will be important in helping to check the predicted climatic responses from climate models against actual observations of climate behavior in the next several decades.

D. Other Carbon Cycle Research Needs

Since it is not possible to cover all research activities and associated needs in one set of congressional testimony, I have attempted to highlight what are believed to be the most critical issues and ask that you refer to the DOE Carbon Cycle Research Program Plan (December

1983) as a detailed source of additional information on this subject. Further refinement of this plan is not expected until after the SOA Report on the global carbon cycle has been completed. Some additional key research efforts which have been identified are:

- Evaluation of CO_2 exchange between atmospheric and oceanic and biospheric sources and sinks from interpretation of atmospheric CO_2, carbon isotope ratios, and three-dimensional atmospheric tracer modeling.

- Expansion of ice core research effort following acquisition of new high-resolution cores.

- Development and implementation of CO_2-gas standard reference materials.

- Data bases on fossil fuel releases and refinement of energy/economic models for future fossil fuel use projections.

- Develop data base for atmosphere/ocean exchange of CO_2 for regions/seasons not amenable to conventional sampling techniques.

- Estimate anthropogenic changes in fluxes of nutrients/carbon to oceans and in carbon sink in continental shelf sediments.

- Use analyses of ^{14}C tracer profiles in soils to estimate potential carbon losses from disturbance.

- Estimate changes in carbon fluxes from terrestrial ecosystems produced by climate change.

- Develop and refine global carbon cycle models, produce library of existing models and projections of future atmospheric CO_2 levels.

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E. Climatic Impact of Atmospheric Constituents Other Than CO_2

A number of trace gases that have significant anthropogenic sources also have strong infrared absorption bands and can theoretically contribute to the atmospheric greenhouse effect associated with increasing CO_2. Several of these chemical species have exhibited significant increases in atmospheric concentrations during the period of the Mauna Loa CO_2 record (and, by inference, during the industrial era). In this group are the long-lived atmospheric constituents: nitrous oxide (N_2O), methane (CH_4), and the chlorofluorocarbons (Freons, a diverse group of substituted methanes and ethanes used as refrigerants and as aerosol propellants).

The interplay of fossil fuel, biomass burning, and a combination of other natural and anthropogenic sources controlling the atmospheric concentrations of N_2O and CH_4 (and their reaction products) is only poorly understood. Projections of future behavior of these species are thus even more difficult than for CO_2 and are further complicated by the occurrence of photochemical reactions with each other and with other natural chemical constituents. Some of the reactive by-products, notably of the Freons and N_2O, act as catalysts in the destruction of the radiatively important ozone (O_3), while photochemical reactions of CH_4 (and CO_2) are believed to increase O_3 levels (Andreae et al. 1982; Bolin et al. in press; Fraser et al. 1983; Kerr 1983; Khalil and Rasmussen 1983; Rasmussen and Khalil 1983; Weiss 1981).

Although projections of radiatively important trace gases (or ozone-controlling reaction products) are not included in the present scope of the Carbon Cycle Research Program because the existing budget is dedicated to resolving the aforementioned carbon cycle questions, it should be recognized that the presence of the trace gases could significantly augment the predicted climatic response due to CO_2. This might be of particular significance if trace gas concentrations continue to increase at rates observed over the past several decades and if fossil fuel CO_2 releases continue at the reduced rates observed over the past several years (Kerr 1983; Marland and Rotty 1983).

F. Linkages Between Biogeochemical Cycles

Patterns of land use and associated temporal changes being defined by the Global Carbon Cycle Program have a direct bearing on the source of several of the trace atmospheric constituents (e.g., CH_4 and N_2O). Likewise, the biogeochemical cycle of nitrogen affects the biogeochemical cycle of carbon both in terrestrial and oceanic systems because of nitrogen's well-known nutrient status. Other chemical elements (e.g., phosphorus and sulfur) also can have a significant impact on the carbon cycle. Thus, to some extent, reductions in the uncertainties associated with our understanding of the global carbon balance require that we understand the relationships or linkages between the carbon cycle and other critical element cycles on a global scale. It is timely that we begin to address these issues in order to develop the more robust multi-element global biogeochemical models which will be needed to fulfill the entire need for climate response projections. This is preferable to an approach which treats the sources of the individual atmospheric constituents in total isolation from one another. Knowledge about the global chemistry of nitrogen and sulfur will also be valuable for other research activities, e.g., the acidic precipitation question.

G. Value of Research Plans and Role of Innovation

A research plan provides focus for a structured research program by clearly identifying the applied objectives, defining pragmatic issues in rigorous scientific terms, and outlining the research strategy required to resolve the issues. Such a plan becomes a valuable tool for communication, especially when the issue(s) is complex, uncertain, and controversial. A research plan also ensures the most effective use of scientific knowledge and resources.

Yet documentation of research needs and research plans should not be misconstrued as an inflexible agenda. Scientific creativity and innovation will continue to be essential ingredients to this effort. Currently unperceived approaches may result in significant breakthroughs in our technical understanding of the problems and issues. The present DOE research plan is already a product of earlier plans that have evolved as our knowledge base has increased; it is a dynamic document that has been, and will continue to be, reshaped to reflect the consensus of the scientific community. We expect the 1985 SOA Report on the global carbon cycle to provide another source of information for identification of research needs, and for further definition and refinement of certain key program areas, e.g., a core oceanic measurements effort.

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IV. RESEARCH PROJECTS IN THE ORNL GLOBAL CARBON CYCLE PROGRAM

The deployment of DOE's Global Carbon Cycle Program has led to a significant expansion in the number of extramural participants at universities and other research laboratories. Since our program is still in a transitional state, a further expansion is expected. A listing of relevant institutional affiliations, research topics, and principal investigators' names for fiscal year 1984 is provided in Table 1. The projects and investigators associated with intramural research at ORNL in fiscal year 1984 are listed in Table 2.

Extramural Research

Many of the subcontracts listed in Table 1 are relatively new, and, thus, research results are not yet available. Results from some projects are described along with accomplishments from ORNL in-house research. The following are descriptions of projects, recent accomplishments, and pertinent references from the remaining subcontracts.

Study of CO_2 Source/Sink Distributions with a 3-D Model (I. Y.-S. Fung and D. Rind).

Information on the sources and sinks of atmospheric CO_2 is contained in the geographical, seasonal, and interannual variations of the global atmospheric CO_2 distribution. The measured concentrations of CO_2 at several locations illustrate large variations in the amplitude and phase of the seasonal cycle superimposed on an increasing secular trend. Recent analysis of the CO_2 records reveals that the amplitude of seasonal cycle has detectable interannual variations and may be increasing in time. This study is a modeling effort to study the prospects of extracting some of the potential information on CO_2 sources and sinks from the observed CO_2 variations. The approach is to use a three-dimensional (3-D) global transport model, based on winds

Table 1. Extramural Subcontractors in the DOE Global Carbon Cycle Program at Oak Ridge National Laboratory

Institution	Investigator	Project Title
Columbia University	W. S. Broecker	Ocean Tracer Modeling
Columbia University	I. Y.-S. Fung	Study of CO_2 Source/Sink Distributions with a 3-D Model*
Cornell University	C. A. S. Hall	Merging the Tropical Biosphere Model and Carbon Inventory Estimates with Land-Use Change Estimates
Duke University	J. F. Richards	Land Use and Vegetation Changes in South and Southeast Asia, 1700-1980 AD
Duke University	W. H. Schlesinger	Arid Zone Soil Carbonates in the Global Carbon Cycle
Duke University	W. H. Schlesinger	Changes in the Flux Rates of the Soil Carbon to the Atmosphere Due to Disturbance
Marine Biological in Laboratory	R. A. Houghton	Mathematical Models for Use Defining the Role of the Terrestrial Biota in the Global CO_2 Cycle
Marine Biological	G. M. Woodwell	Test of the Use of Satellite Imagery to Detect Changes in the Area of Forests in the Tropics
NASA Goddard Space Flight Center	D. Rind	Study of CO_2 Source/Sink Distributions with a 3-D Model*
Oregon State University	C.-T. A. Chen	On the Increase of Total CO_2 in the World Oceans

Table 1. (Continued)

Institution	Investigator	Project Title
Scripps Institution of Oceanography	R. B. Bacastow**	Development of a Three-Dimensional Model of the Natural Carbon Cycle in the Ocean and Its Perturbation by Anthropogenic CO_2
University of Arizona	A. Long	Accurate Determination of $^{13}C/^{12}C$ in CO_2 of Past Atmospheres from $^{13}C/^{12}C$ in Tree Rings by Removal of Climatic Interferences
University of Illinois	S. Brown	The Role of Tropical Forests in the Global Carbon Cycle*
University of Oklahoma	R. J. Mulholland	Using the Airborne Fraction as an Index for Comparing Model Response with Atmospheric CO_2 Data
University of Puerto Rico	A. E. Lugo	The Role of Tropical Forests in the Global Carbon Cycle*
University of Washington	M. Stuiver***	Geochemical Determination of Biospheric CO_2 Fluxes to the Atmosphere

*Joint Project.

**Currently at the Max-Planck Institute, Hamburg, Federal Republic of Germany.

***Currently at the University of Heidelberg, Heidelberg, Federal Republic of Germany.

Table 2. ORNL Intramural Research Projects in the DOE Global Carbon Cycle Program

Project/Activities	Investigators
Global Carbon Cycle and Climate	
• Carbon Cycle Model Development	W. R. Emanuel
Terrestrial Ecosystems	C. F. Baes, Jr.
Oceans	D. L. DeAngelis
Sensitivity/Uncertainty Analysis	R. H. Gardner
CO_2 Projections	G. G. Killough, Jr.
• Terrestrial Ecosystem Data Analysis	A. W. King
Mapping Global Carbon	J. S. Olson
Ecosystem Characterization	T.-H. Peng
Changes in Land Use	A. M. Solomon
Climate Feedbacks	
Soil Carbon in the Global Carbon Cycle	
• Simulation Modeling	W. M. Post
Natural Vegetation Fluxes	L. K. Mann
Response to Disturbance	J. J. Pastor
Nitrogen Linkage	H. H. Shugart
• Analysis of Shifts in Soil Carbon	
Varied Historical Data Sources	
Develop New Data in Tropics	
Turnover Rates-^{14}C Tracer	

from a 3-D general circulation model (GCM), to advect CO_2 noninteractively, i.e., as a tracer, with specified sources and sinks of CO_2 at the surface. If the model can reproduce the general character of observed CO_2 variations on the basis of physically justified sources and sinks, it may then be used for experiments to determine the sensitivity of the global CO_2 distribution to various assumptions about CO_2 sources and sinks. It is anticipated that this approach may lead to useful quantitative limits on some CO_2 sources and sinks.

Recent Accomplishments

- Large longitudinal variations exist in the atmospheric CO_2 distribution. A 3-D modeling approach is necessary to study the global carbon cycle. Large simulated amplitudes in atmospheric CO_2 at certain continental locations cannot be confirmed presently by atmospheric CO_2 observations due to lack of measurements.

- Results demonstrate that more realistic, e.g., detailed, models of the terrestrial system, incorporating seasonal behavior, are needed for analyses of the global carbon cycle.

- Model simulation which indicates that most of the recent fossil fuel uptake by the oceans has occurred in the Northern Hemisphere.

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Role or Tropical Forests in the Global Carbon Cycle (S. Brown and A. E. Lugo)

All principal carbon sources and sinks in the global carbon cycle must be identified, quantified, and documented in order to permit the development of accurate models for projecting future atmospheric CO_2 concentrations. Because CO_2 fluxes associated with tropical forest disturbance and recovery are poorly known, evaluation of available information and new data generated by this project will add greatly to the present data base used to predict carbon fluxes from the terrestrial biota. One aspect of the research involves analyses of field data on tropical soils in contrasting environments in Central and South America.

Recent accomplishments

- Data from Puerto Rico indicate that continuous agriculture depletes soil carbon by a greater fraction of the original amount in humid climates that in arid ones.

- The rate of soil carbon accumulation through forest succession after abandonment occurs at approximately the same relatively fast rate in both humid and arid environments.

- Carbon accumulates in soils under lands in pasture for many years to level approaching that of the original forest.

- The total carbon pool in tropical forest vegetation is 100 x 10^9 t giving a weighted carbon density of 52 t/ha, or about one-half that previously reported - results in less CO_2 production when tropical forests are cleared; also raises questions about the size of the global terrestrial carbon pool.

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Merging a Tropical Biosphere Model and Carbon Inventory Data with Estimates of Land-Use Change (Charles A. S. Hall)

One of the chief remaining sources of uncertainty for both past and present estimates of carbon release to the atmosphere is past patterns of land use. This research consists of developing a comprehensive, flexible, and transportable computer model designed to quantify the carbon exchange that occurs as land is subjected to different uses over time. The work has been focused on the tropics but the model is readily adaptable to other environments. Various existing data on carbon content of vegetation and soils, and on land-use change, were synthesized into formats compatible with the model.

Recent accomplishments

- Model results from data from 51 tropical countries indicate that it is unlikely for carbon release to exceed about 2 x 10^{15} gC per year. Actual estimate was 0.6 x 10^{15} g carbon per year - consistent with earlier analyses by Hall that suggest that land-use change in the tropics results in a modest release of carbon to the atmosphere.

- Evidence indicates that land use does not greatly affect soil carbon below 40 cm - assuming carbon readily exchanges with the atmosphere at deeper depths may overestimate the release of carbon due to disturbance of terrestrial ecosystems.

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The Transfer of Biospheric Carbon to the Atmosphere Indicated by Pacific Coast Tree Ring Records Corrected for Growth Rate Effects (M. Stuiver).

The magnitude of the net biospheric CO_2 flux to the atmosphere during the current millenium can theoretically be derived from the historical record of carbon isotope ratios ($^{13}C/^{12}C$). This study uses tree ring isotope records to detect changes in atmospheric CO_2 isotope ratios because wood cellulose, observed as annual tree rings, incorporates carbon from the atmosphere, and hence reflects the isotope ratio of atmospheric CO_2 for that year of growth. Part of the variability in ^{13}C fractionation is being corrected by normalizing on constant growth rates using changes in ring areas and ring widths.

Recent accomplishments

- An estimated amount of 90 x 10^{15} g of biospheric carbon was released between 1800 and 1975.

- Atmospheric CO_2 level for the year 1600 was equal to 268 ppm, and averaged 276 ppm from A.D. 235-1850; these values, based on data from Pacific coastal sites, differ from those generated from European data - additional studies are needed to identify and eliminate the sources of variability.

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New Evidence from Carbon Isotopes in Tree Rings from the Southwestern United States: Removal of Climatic Interferences (S. W. Leavitt and A. Long)

Contributing to some of this divergence in tree ring reconstructions of atmospheric CO_2 levels are site selection, the wood component chosen for analysis, environmental influences on fractionation, and natural intra-individual and intra-site isotopic variability. A previous study was aimed particularly at eliminating both climate effects on isotopic fractionation and the radial isotopic variations within individuals, as contained in a 50-year juniper tree-ring record from Arizona, U. S. A. Present research examines a much longer set of $^{13}C/^{12}C$ measurements from pinyon pine trees growing at sites in the southwestern United States.

Recent accomplishments

- Gross factors affecting the whole site (e.g., temperature, rainfall) generally seem to influence individual isotope ratios more than do other specific influences (e.g., competition, heredity).

- The corrected pinyon pine record suggests a relatively small change in atmospheric CO_2 from biospheric contributions over the past 180 years. It also suggests a previously neutral biosphere which has become a net carbon sink over the last 50 years.

- Results are quite distinct from those of European trees; errors may be further reduced if the natural variability of isotope ratios in and among trees is known and considered in the sampling process.

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Arid Zone Soil Carbonates in the Global Carbon Cycle (W. H. Schlesinger)

The soils of arid and semiarid ecosystems store carbon in inorganic form, primarily as calcium carbonate. This secondary carbonate occurs in a variety of forms, ranging from precipitates in the interstitial spaces of the parent material (caliche or calcic horizons) to almost pure, laminated layers of carbonate (calcrete or petrocalic horizons). Although some of these deposits are very old, carbonate precipitation is also a present day pedogenic process. Therefore, it is important to understand the role of natural formation of arid zone soil carbonates in the global carbon cycle.

Recent accomplishments

- The rate of carbon storage in caliche formation ranges from 0.2 to 0.4 $gC/m^2/yr$.

- Carbonate precipitates in arid soils as a result of evaporation of water from the soil profile, and not as a result of an interaction of root respiration by desert plants with the soil carbonte equilibrium.

- Carbonate precipitation in arid soils is as high as 1.4 gC/m^2yr in some soils of southern New Mexico.

- Results indicate that an earlier, preliminary estimate of a worldwide flux of 2.3×10^{13} gC/yr for the storage of carbon in desert caliches is not likely to change radically - the existing source term for carbon flux in desert soils is generally acceptable unless anthropogenic activities (e.g., cultivation, irrigation) affect this natural precipitation process.

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Schlesinger, W. H. 1982. Carbon storage in the caliche of arid soils: case study from Arizona. Soil Science 133:247-255.

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Intramural Research

The Global Carbon Cycle and Climate (W. R. Emanuel et al.)

The global carbon cycle is being studied to evaluate the mechanisms that control changes in atmospheric CO_2 concentration. The oceans are the primary sink for excess carbon from the atmosphere. Historically, terrestrial ecosystems have been a source of CO_2 in addition to fossil fuels. By quantifying interactions between the atmosphere and these other reservoirs, this research provides a basis for projecting future CO_2 concentrations as fossil fuel use and other perturbations to the carbon cycle continue. Mathematical models of the carbon cycle, assembled from representations for each component and tested against available independent data, are primary tools in this effort. In the next stages of research, emphasis is on improving reconstructions of changes in carbon storage in vegetation and soils by incorporating geographical detail in the analysis of land-use change. Ocean models are being refined by giving explicit treatment to each major region of the oceans and by resolving both latitude and depth. These refinements may improve the consistency of estimates of carbon releases, rate of uptake by the oceans, and the observed increase in atmospheric CO_2, making future CO_2 projections more reliable.

Recent Accomplishments

- A data base of carbon density and areal extents for the world's major ecosystems has been developed. The data base and accompanying computer map (in color) describe contemporary carbon conditions of the living terrestrial biosphere. A summation [0.5° x 0.5° (latitude, longitude) resolution grid] produces a global estimate of 560×10^{15} grams (560 gigatons) of carbon in contemporary live vegetation.

- A computerized map of the natural distribution of major terrestrial ecosystem complexes has been completed. Estimates of carbon density in vegetation and soils have been combined with this map to estimate pre-civilization terrestrial carbon storage. Carbon storage in live vegetation under natural conditions was approximately 1000×10^{15} g compared to 560×10^{15} under contemporary land use.

- Work to develop compartment models for each major biome or ecosystem complex continues. These models simulate the impact of disturbance on carbon storage in vegetation and soil as well as carbon cycling and exchange under natural conditions. Terrestrial seasonal simulations for two types of temperate and two types of tropical forests have been implemented as computer models, and more are planned in the near future. A literature review of background data for developing a set of terrestrial models has been completed.

Ocean Model Development

- Five two-dimensional models that simulate ventilation of the temperate North Atlantic have been developed. The basic structures of these models are similar in that the upper thermocline is divided into three isopycnal horizons each with its own outcrop at high latitudes. The circulation patterns and ventilation pathways for each model correspond to alternative extreme assumptions on ventilation for this region. The thermocline models were calibrated against the observed distribution of tritium assembled by the GEOSECS survey and used to simulate the distributions of a number of tracers including ^{3}He, ^{14}C, radiokrypton, and Freons.

- Comparisons of responses and tests against data suggest that the information carried by the distributions of multiple tracers may not be sufficient to distinguish among thermocline models. Differences in estimates of the uptake of CO_2 by these models are small, and simulated uptake of excess CO_2 by two-dimensional isopycnal models with polar outcrops is not significantly different from that simulated by a one-dimensional vertical mixing model without polar outcrops.

- A two-dimensional box model of the oceans that emphasizes carbon chemistry and the role of marine organisms has also been developed. The most extensively studied version of the model uses 91 boxes arranged to form ten isothermal horizons ranging in temperature from 1.5°C to 24°C. Initial work has concentrated on testing the sensitivity of steady states to assumptions on parameter values and boundary conditions.

- A modified globally averaged box-diffusion model that includes biological activity, nutrient cycling, upwelling, new deep-water formation, and separate vertical mixing rates for the upper thermocline and the deep sea has been developed. The total uptake of CO_2 simulated by a set of box-diffusion models calibrated for different regions of the ocean is essentially the same as that predicted by the original global box-diffusion model of Oeschger et al. (1975). However, the modified box-diffusion model predicts an uptake about 25% higher.

- In collaboration with W. S. Broecker of Lamont-Doherty Geological Observatory, the Redfield ratios of major nutrients in the oceans have been reevaluated on the basis of chemical data collected by the GEOSECS and TTO programs. Commonly used values of the Redfield ratios (1:16:106:138 - P:N:C:O) are revised to 1:17:133:177.

Projecting Atmospheric CO_2 Concentration

- A globally averaged carbon cycle model was formulated for projecting atmospheric CO_2 concentration for alternative scenarios of future fossil fuel use. The computer implementation of this model is described in Emanuel et al. (in press). Projections for scenarios developed for the DOE by staff of the Institute for Energy Analysis are described in a contribution to a forthcoming DOE report on energy scenarios and CO_2 projections.
- To clarify the dependence of CO_2 projections on model assumptions and parameter values, sensitivity and error analyses were carried out. As expected for this model formulation, the greatest sensitivity is to assumptions on surface water chemistry and parameter values controlling transfers to deep-water layers; however, in simulations that include substantial historical releases of carbon from terrestrial ecosystems, factors that control the magnitude of the net terrestrial release are critical.

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*Joint DOE/NSF support.

Soil Carbon in the Global Carbon Cycle (W. M. Post, J. Pastor, L. K. Mann, and H. H. Shugart)

The ultimate objectives of this project are two-fold: (1) identify factors important in influencing the variation in carbon density in the important soil carbon pools, and (2) determine the change in flux rates between the soil carbon pool and the atmosphere when natural ecosystems are converted to managed use. The first objective requires coupling a forest floor carbon model to a forest vegetation production model. This coupling will allow analysis of the relationships between forest type, management practices, and composition on soil carbon density and turnover time in both temperate and tropical forests. The second objective involves compilation and review of literature information and primary data needed for model development regarding changes in soil carbon storage due to management. This research consists of two approach (a) analysis of soil carbon content from experiments where paired plots, one natural and one manipulated, were remeasured at intervals over long periods of time; and (b) statistical analysis of a large number of soil profiles which are not paired, but prior to disturbances were similar. The feasibility of using ^{14}C tracer methodology in directly measuring soil carbon changes is also being assessed.

Recent Accomplishments

- An analysis of the scientific literature concluded that the loss of carbon from soil profiles upon cultivation is about 30% over a 20- 50-year interval. This value is lower than parameters used in most recent models of anthropogenic changes in the global carbon cycle. Different ecosystems showed different soil carbon losses upon conversion. Temperate forests showed a mean loss of 34% of the original carbon content. Temperate grasslands lost 29%. In tropical ecosystems where secondary forests are converted to short-term agriculture, a mean loss of

21% was found. The quality of the available data generally precluded any analysis of the loss of carbon as a function of time since disturbance. Changes in ^{14}C age and C/N ratio with cultivation are consistent with a rapid loss of labile organic materials during the first 20 years after land-use conversion, followed by a slower loss rate with continued agriculture.

Data on 322 soil profiles from Soil Survey Investigation Reports of the U.S. Department of Agriculture were analyzed and classified into soil groups, vegetation types, and cultivation categories to eliminate variation from factors related to climate, soil texture, parent material, and cultivation. Mean values suggest that cultivated Alfisols contain 33% less carbon than uncultivated Alfisols. Apparent losses from cultivated Mollisols are much less; the data from the Udoll suborder suggest no change in carbon content to 150 cm depth in cultivated profiles. There is, however, a change in distribution of organic matter in these profiles. Surface horizons average 30 to 50% less carbon while lower horizons show gains in carbon. This suggests that cultivation may increase downward transport of organic matter in these soils.

In both of these studies, lower amounts of carbon loss due to cultivation are reported than those of previous investigations. This is largely due to differences in treatment of the data and sampling approaches. Most previous studies reported only percentage carbon loss in the surface soil (less than 20 cm) where bulk density is low and only a portion of the total organic matter is stored. In this study, carbon storage was analyzed in profiles to one meter in depth where increases in soil bulk density, mixing into lower layers, and increased downward transport during cultivation were taken into account.

- Initial development of a computer model for soil and litter decomposition has been completed. The model is designed to link forest production to soil carbon storage, and takes into account nutrient availability and climatic factors. The ultimate goal is a model which can predict changes in soil carbon when forests are converted to agricultural and other uses.

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V. OTHER CARBON DIOXIDE RESEARCH AND SUPPORT ACTIVITIES AT ORNL

Terrestrial Ecosystems, Climate, and the Global Carbon Cycle (W. R. Emanuel, A. M. Solomon, T. J. Blasing, G. G. Killough*, J. S. Olson, T.-H. Peng, W. M. Post, R. J. Renka**, J. A. Watts, and D. C West, Environmental Sciences Division)

This research project is supported by the National Science Foundation (NSF). A major effort has involved development of a computerized map of the world's life zones to serve as the geographical basis for spatially disaggregated, climate-dependent models for the terrestrial component of the global carbon cycle. Data for calibration of models for carbon cycling in each life zone are being assembled and organized according to the Holdridge Life Zone Classification System.

This data base is used to analyze relationships between climate and terrestrial carbon cycling with recent emphasis on soil carbon storage.

A procedure for calibrating a two-dimensional (latitude and depth) model of carbon turnover in the world's oceans has been implemented. Initially, this approach is being tested in the Atlantic Ocean. A major review of tracers in the oceans has been completed, resulting in an improved understanding of the use of multiple tracers in studying the dynamics of carbon in the ocean. Aggregated models of the carbon cycle continue to be refined and are being applied to the interpretation of $^{13}C/^{12}C$ time series.

Stochastic forest stand growth and succession models are being used in conjunction with pollen records of vegetation composition. Current emphasis is on testing hypotheses which seek to explain anomalous biotic assemblages during prehistoric periods when the seasonal thermal wave apparently was much reduced. Biomass values simulated from pollen records are being independently verified by directly estimating modern tree species abundances from pollen influx in lake sediments. Tree-ring chronologies are being used to reconstruct climate over the past 200-300 years as an input to the stand growth models. Efforts to collect new Holocene pollen records have been concentrated in the area of central Kentucky to southern Ohio.

Recent Accomplishments

- Analysis of the distribution of terrestrial ecosystem complexes through the application of climate-based classification schemes*
- Mapping of the contemporary distribution of major terrestrial ecosystem complexes and associated carbon storage in vegetation and soils*

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*Health and Safety Research Division
**Computer Sciences Division

- An analysis of the alterations to broad zones of ecosystem complexes from climate change projected for elevated atmospheric CO_2 concentration*

- Clarification of the relationships between climate and carbon storage in soils*

- A compartment modeling system to simulate carbon cycling in major ecosystem complexes*

- Demonstration that forest stand simulation models are consistent with fossil pollen records on time periods ranging from 10,000 to 20,000 years

- Forest simulations of Holocene vegetation history in eastern North America construined by pollen records

- Completion of a tree-ring sampling program in Illinois, Iowa, and Missouri and the development of schemes to reconstruct climatic variables from eastern North American tree-ring data

- A major review of the interpretation of tracers in the oceans*

- Ocean models based on tracer data that consider variations with both latitude and depth*

- Interpretation of $^{13}C/^{12}C$ time series from tree rings in terms of the historical release of carbon to the atmosphere from terrestrial ecosystems*

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*Joint DOE/NSF support

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*Joint DOE/NSF support

Carbon Dioxide Information Center (M. P. Farrell, et al.; Information Division)

The Carbon Dioxide Information Center (CDIC) was established at ORNL by DOE to develop and maintain a data management and network system that serves scientists, administrators, and legislators involved in understanding and resolving the CO_2 issue. The broad objectives of CDIC are to:

- identify and highlight data needs and priorities;
- recognize other important national and international data collection activities, providing network referral and follow-up;
- collect, organize, process, evaluate, package, and disseminate numeric, bibliographic, and other related CO_2 information (e.g., computer models, benchmark analysis results); and
- develop and implement procedures to ensure quality of numeric data supporting the CO_2 assessment effort.

Recent Accomplishments

CDIC currently has:

- more than 1650 individual participants in CDIC Network, representing 44 countries;
- more than 7200 citations with keywords and work breakdown categories;
- 89 data bases inventoried and described; and
- 29 data bases (21 climate; 8 carbon cycle) acquired.

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Climatic Analysis of Simulated Weather Patterns (T. J. Blasing, Environmental Sciences Division)

The primary purpose is to develop and implement a strategy for comparing model predictions of climate with observed climate. The study will not only assist climate modelers in diagnosis and improvement of model performance, but will benefit climate-model users by determining which climatic factors are most useful for climate-impact studies. An additional objective of the study is to evaluate the use of climate-model output for determining impacts of a CO_2-induced warming on the North American corn belt. Past research (by A. M. Solomon) also dealt with modeling of responses of forest ecosystems to projected climate shifts.

Recent Accomplishments

- Predicted response of the North American corn belt to climatic warming - net northward movement without major problems if appropriate planning/response measures implemented

- Implications from Twentieth Century climatic anomalies for future CO_2 induced climatic warming - first detection of CO_2 signal expected in summer weather patterns.

- Model simulations predict net decreases in carbon storage capacity of eastern North American forests from climatic warming - losses offset any potential increases from CO_2 fertilization or growth enhancement in Canadian boreal forests.

Recent References

Blasing, T. J. and G. R. Lofgren. 1980. Seasonal climatic anomaly types for the north Pacific sector and western North America. Mon. Weather Rev. 208:700-719.

Blasing, T. J. 1981. Characteristic anomaly patterns of summer sea level pressure for the Northern Hemisphere. Tellus 33:428-437.

Blasing, T. J. and A. M. Solomon. 1983. Response of the North American corn belt to climate warming. TR-006. U.S. Department of Energy, Washington, D. C.

Solomon, A. M. and M. L. Tharp. Transient Response of Unmanaged Forests to CO_2-Induced Climate Change in Eastern North America: Available Approaches, Initial Results, and Data Demands. ORNL/TM-9078. Oak Ridge National Laboratory, Oak Ridge, Tennessee (in press).

Elevated CO_2 Effects of Terrestrial Ecosystems (R. J. Luxmoore, R. J. Norby, A. M. Solomon, and D. C. West; Environmental Sciences Division)

The overall objective of this research is to determine how elevated atmospheric CO_2 concentration affect forest ecosystems. This will be accomplished through both empirical and computer-simulation studies. Nutrient retention and phytomass of forest ecosystems are being studied in controlled environmental chambers. Specific studies examine plant root-mycorrhizal system and soil microbial responses to elevated CO_2. Computer simulation studies will determine how forests respond directly to elevated levels of atmospheric CO_2. Secondary climatic effects of elevated CO_2 will also be modeled, including pathogenic insect infestation, soil nutrient turnover, and temperature/moisture responses by trees as a function of soil variability.

Recent Accomplishments

- Fabrication of test facilities for controlling plant exposure CO_2 atmospheres.

- Initial results indicate increased root exudation and reduced loss of some nutrients at higher CO_2 levels.

Sensitivity Analysis of the Impact of CO_2 Accumulation on Climate (M. C. G. Hall and D. G. Cacuci; Engineering Physics Division)

Despite the complexity of the computer models used to predict CO_2-induced climate change, these models contain many gross approximations. The goal of this DOE-supported research is to develop an efficient method of estimating the effect of approximations in climate models. Research was initiated using a simple climate model (radiative-convective type), and is now continuing using the most sophisticated type of climate model (a global general circulation model). Such sensitivity analyses will enable climate modelers to identify the most important areas for model improvement and will help decision makers understand the reliability of the predictions of CO_2- induced climate change.

Recent Accomplishments

- Sensitivity analysis of a radiative-convective model by the adjoint method - demonstrated that the effect of a wide variety of approximations can be estimated using computing time equivalent to only one model rerun.

Recent References

Hall, M. C. G., D. G. Cacuci, and M. E. Schlesinger. 1982. Sensitivity analysis of a radiative-convective model by the adjoint method. J. Atmo. Sci. 39: 2038-2050.

Hall, M. C. G. and D. G. Cacuci. 1983. Physical interpretation of the adjoint functions for sensitivity analysis of atmospheric models. J. Atmo. Sci. 40: 2537-2546.

CO_2 Research in ORNL's Energy Division

Energy Supply and Demand Implications of CO_2 (A. M. Perry and W. Fulkerson, with assistance from scientists at the Massachusetts Institute of Technology and Institute for Energy Analysis, Oak Ridge Associated Universities)

The purpose of this DOE-supported study was to investigate the required timing of actions to limit the growth of atmospheric CO_2 under various assumptions concerning the future, unregulated use of fossil fuels, worldwide, and concerning the maximum acceptable levels of CO_2 in the atmosphere. The work was undertaken, in part, in response to claims that immediate and severe restrictions on the use of fossil fuels would be required in order to avert potentially serious climatic changes.

Recent Accomplishments

- The marked reductions in the growth rate of global carbon emissions that has occurred in the past ten years has significantly reduced the urgency for any CO_2-related restrictions on fossil fuel use - if growth rates of carbon emissions remain in the vicinity of 2%/yr., as now seems likely, then actions to limit the further increase of CO_2 would not be required in this century.

- High growth rates of the nineteen-fifties and -sixties could not be maintained if there were any serious intent to limit CO_2 to roughly twice its 1900 level, i.e., to around 600 ppm.

Recent Reference

Perry, A. M., K. J. Araj, W. Fulkerson, D. J. Rose, M. M. Miller, and R. M. Rotty. 1982. Energy supply and demand implications of CO_2 Energy 7:991-1004

Atmospheric Retention of Anthropogenic CO_2: The Scenario Dependence of the Airborne Fraction (A. M. Perry).

The purpose of this study, supported by the Electric Power Research Institute (EPRI), was to illustrate and to explore further the already-recognized dependence of the airborne fraction on details of the projections for future CO_2 production, i.e., fossil fuel use. Several carbon cycle models were used in this exercise.

Recent Accomplishments

- The airborne fraction, presently about 0.6 or less, depending on the biosphere contribution (still poorly defined), may increase in the future, stay nearly the same, or decrease, depending on the future CO_2 production rates from fossil fuels.

Recent Reference

Perry, A. M. Atmospheric Retention of Anthropogenic CO_2: The Scenario Dependence of the Airborne Fraction. Electric Power Research Institute, Palo Alto, California (in press).

The CO_2 Issue: Potential Implications for U. S. Electric Utilities (A. M. Perry).

Growth in electricity-generating capacity in the United States will, for some years, be based mainly on coal-fired plants. The purpose of this EPRI-supported study was to explore the timing of a gradual swing away from coal to non-fossil energy sources that might be required if a serious global effort were undertaken to limit the future increase in atmospheric CO_2. Result of this study have not yet been reviewed by EPRI, and no conclusions can yet be drawn.

Mr. GORE. Well, thank you very much. That's a most impressive statement, and the work you all have been doing is most impressive as well. I will hold questions until the other panelists have concluded. Let me call now on Dr. Wallace Broecker from the Geochemistry Department at Lamont-Doherty Observatory in Palisades, NY. Dr. Broecker, welcome. We are delighted to hear from you.

STATEMENT OF DR. WALLACE BROECKER, GEOCHEMISTRY DEPARTMENT, LAMONT-DOHERTY OBSERVATORY

Mr. BROECKER. Well, thank you, Mr. Gore.

I guess what I would like to emphasize today is that the problem we face I think long term is a very serious and challenging one, and I don't think that right now the world is doing the proper research in order to get the answers we are going to need on the time scale we need them, so I have to defend these statements. I will start by trying to show you why I believe we are facing very important changes due to the buildup of these CO_2 and other greenhouse gases, and that many of these changes are things that we are not likely to easily predict. I think that the present models we're using tend to oversimplify things and perhaps give us a more conservative view of the future.

Now my training is in geochemistry. I have spent an academic career of 30 years working on carbon cycling, ocean circulation, and paleoclimate, so I have spent my life studying the very thing that we are interested in from, I think, all points of view. Now in my own thinking the very important information we have with regard to what's coming in the future is to look at the past. We have now accumulated a rather impressive set of data about times of the past when climate was very different than now.

Most important in that data set, perhaps, is the material shown on the map in my testimony which shows the way the world looked 18,000 years ago during the glacial period compared to today. It's a simplified map showing ice, forests, and other types of land, and you notice that during the glacial period the forests are dramatically down, maybe a factor of 5. The ice is much larger, and indeed paleoclimatic records show that every place you can look on Earth where you can find sediments of that age, things were very different.

Now the amazing thing about this is that over the last decade or so people have made a very strong attempt to find out how much colder it was there, and they have come up with the rather startling conclusion that during the time shown on this map the temperature of the globe was only about 8 degrees cooler than it is now—I mean, I'm sorry, 4 to 5-degrees cooler than it is now, so that the cooling of the Earth that produced these glacial periods is comparable in magnitude to what we expect from the full CO_2 effect.

So I think our most impressive information with regard to how much the environment of the planet changes per unit temperature change is shown by these maps, and if they are any valid prediction of what is going to go on in the future, that means that a 4- or 5-degree temperature change is not at all trivial. It goes well beyond our intuition and it will, you know, make the Earth a very different place to live.

Now by "different" I don't mean bad. That's one of the unfortunate things. We are not in a position to say, really, I don't even think the net balance of these changes. What I want to stress is, the changes will be large, and we're going to have to accommodate the bad parts and we're going to have to try to take advantage of the good things, but we have to look ahead to do that.

Now recent work on the paleoclimatic record, some startling results have been obtained from long ice cores that have been drilled through both Antarctica and Greenland. The latest core in Greenland was at a site called DI-3. It's one of our radar bases in southern Greenland. This showed that during the last glacial period there were a series of very sharp climatic changes that took climate well back toward its interglacial or present condition. These were, even by interglacial to glacial standards, very large changes.

People have looked at these records in the ice—and there are a few pollen records that show similar detail—and sort of in the past considered that perhaps these were just local events, noise in the record, but a startling finding by the workers in Bern, Switzerland has shown that that is probably not at all true. These ice cores contain a record of the past CO_2 content, and they have been able to show that these events that are shown in the middle of this ice core record are associated with large changes in CO_2 content of the air, up to 60 parts per million, and that the one near 1,900-meter depth in this diagram, this happened in less than 200 years.

Now it's not the CO_2 changes themselves that we're concerned about. It's the fact that the only way that we can see that the CO_2 could have changed by that much in that short a time is if there were a rather large reorganization of the way in which the ocean atmosphere system operates; namely, the ocean circulation patterns underwent serious and large changes on a short time scale.

Now it's hard to say whether, by pushing climate into a warmer regime than we have ever experienced, whether we're going to come up against these rapid changes where the system flips from one mode of operation to another. We have really no basis for that. In fact, we can't really prove that they happened in the past, but it does appear to me that these changes are telling us that we have to be concerned that the climate will not necessarily change gradually from conditions we have now to the conditions that we will experience at a full CO_2 warming, but rather they may proceed in jumps, and it's these kind of jumps that would really make things very difficult. We see recently there has been a rapid decline in the state of our forests, many places. This astounds people. I mean, why does it suddenly start to happen so fast? What can we do about it? So man is really the least equipped to cope with very rapid changes when we don't know which way they're going.

Mr. GORE. Let me try to translate what you've just said for my own purposes, and tell me if I am understanding it correctly. You are saying that your study of past atmospheric changes, the ice ages and all the rest, leads you to the conclusion that rather small temperature changes on a linear scale can have the effect of rather quickly throwing the entire global climate system out of equilibrium and pushing it toward a new systemic equilibrium point where the dynamics and the interaction between the different components of that system are very different from the systemic equilibrium which accompanied a temperature just 2 or 3 degrees different from that. Is that——

Mr. BROECKER. That's basically correct, and we're sort of feeling our way in a dark fog.

Mr. GORE. And you're extrapolating from that to say that another change of the same order of magnitude—two, three, four, five degrees—will likely——

Mr. BROECKER. Maybe.

Mr. GORE [continuing]. May, may produce a shift in the systemic equilibrium to a new pattern of interaction. Is that right?

Mr. BROECKER. I guess that's what I'm saying. I'm trying to say that we're dealing with a system that is extraordinarily complicated. We tend to try to model it in a very simple way, and of course our models only permit the simple things that we introduce into the models. The models we make now do not include the ocean in any realistic way; they include it as a heat sink. They may transport heat in the ocean in an artificial way, but they certainly have no way to let the ocean's mode of operation change.

I think all of us think that the next great step that has to be taken, if we're going to be able to improve our ability to predict the future, is to introduce the ocean in a more realistic way into the models, and that means learning a hell of a lot about the ocean that we now don't know. It's difficult. I would say it's comparable to finding the cause of cancer. I mean, it's a very, very, very serious scientific question that's going to require the best minds and a tremendous amount of work.

So just to conclude, I really feel that the present research programs are much too motivated to sort of milk the last possible meaning out of the present information. They are viewed—too much emphasis is being placed on writing a report in 1985, when I think all of us in the field know that in 1985 that report that is going to be written isn't going to be particularly different than the ones that have already been written.

If we are going to make a major advance, we're going to have to buckle down and do some very difficult projects. I think most of us that work in this field have an idea of what those are. I think we agree basically what has to be done. They involve gathering large new data sets that are going to be necessary if we are to make advances. We're going to need that information or we're stuck, and it's going to involve a new generation of models, far more sophisticated and complicated than we have now, in order to get at these things. Too much just playing around now, too little effort to look ahead and say, "What are we going to do?" It's as if we were designing new kinds of beds for cancer patients or something.

That isn't the solution. The solution in the case of cancer was to get at the cell problem, the biochemistry problems, and look at it in a serious way. In the environment we have not done that. We have focused almost entirely on the immediate issues. The science of the environment I think has lagged behind because it has fallen in a crack between the NSF saying, "That is mission-oriented stuff," and mission-oriented people saying, "We've got to respond to immediate problems.

So when I heard 2 years ago that NASA had proposed something called "global habitability," I stood up and cheered because I said that is exactly the kind of program that is needed to get away from the immediate issues, in a way stand back and say what the country needs and the world needs is a very serious program to lay the base for making these decisions we have to make. I think it would be a cost effective thing because God knows how much money we have wasted on environmental issues, largely through our ignorance of how the environment operates, and I don't see that the country has awakened to the fact that it would be cost-effective to do this kind of work.

When I saw the thing about the space platform I about jumped in the Hudson. I thought, you know, for that kind of money one could—if NASA had that kind of money to do satellites that looked back at the Earth, we could for the first time maybe have a hope of finding out about these things rather than just experiencing them in 50 to 100 years. So I am worried and I am concerned, and I think something's got to be done.

Mr. GORE. Well, thank you. Without objection, we will include your full statement in the record.

I don't want to—I said I would save questions until the panel had completed. Let me just interject this one very briefly. On this question of shifting equilibrium points, I didn't quite understand the implications of your testimony for the role of CO_2 in those previous shifts. Was there a particular role assigned to CO_2 in these shifts?

Mr. BROECKER. I think the observation that the CO_2 content of the air trapped in this ice changed indicates to us that the CO_2 content of the atmosphere changed, so we all scratch our heads and say, "How in the heck can you change the CO_2 content of the atmosphere in 200 years by that amount?" We know quite a bit about it, and the people that work on this are pretty much of a mind—I would say totally of a mind—that the only way to do this would be to reorganize the way the ocean/atmosphere system operates and then you might be able to do it.

So we use the CO_2 change not in the sense that we're thinking of it as a causal factor but as an indicator. For the first time there is powerful evidence that the ocean/atmosphere system can reorganize, as you have very nicely stated, into a new equilibrium state. It has done it in the past, and unfortunately we have never been 5 degrees warmer, so it's a guess.

Mr. GORE. So without stating that it's a cause, it is nevertheless possible to say that at each point where we have had a change in equilibrium states, CO_2 densities have been associated with that.

Mr. BROECKER. Yes.

Mr. GORE. Well, I think that's a real good lead-in to Dr. William Jenkins' statement. Dr. Jenkins comes from the Woods Hole Oceanographic Institution at Woods Hole, MA.

We're delighted to have you round out this panel, Dr. Jenkins. Without objection, your full statement will also be included in the record. If you care to present it or summarize any portion of it, feel free to do so.

STATEMENT OF DR. WILLIAM J. JENKINS, WOODS HOLE OCEANOGRAPHIC INSTITUTE

Mr. JENKINS. Thank you.

I would like to follow on a little from what Wally Broecker had mentioned. What I would like to say first of all is to convince you that the oceans play a critical role in the CO_2 climate system in two ways, and then to convince you that in many respects we really do not have a firm handle on how the system will couple together, except in a qualitative way, and then try to convince you that the observational programs that we have at present are inadequate to really address these problems at this stage.

Now I guess the first point is that in many respects the oceans play two roles in the climate system. One of them is, they serve to redistribute heat and temperature and also water vapor, and from this viewpoint this affects the climate system. If you were to look at a given location in the subtropics you would find that half of the heat which is carried between the Equator and the poles as a result of the uneven distribution of energy received by the Sun, half of this heat is carried by the oceans and half is by the atmosphere, and so in a very direct sense the oceans play a very important role in this.

But, more importantly, the oceans in fact will take up the bulk of the manmade CO_2. There is evidence that at present about half of the fossil fuel produced CO_2 has been taken up by the oceans, just by comparing what has been produced with what we see in the atmosphere. What I feel is important about this is reflecting on what Wally Broecker mentioned in terms of nonlinear systems, that is that the climate changes that are going to be caused by CO_2, that have been predicted by the CO_2, in fact may impede the oceans' ability to take up the CO_2.

Most models that are used in the prediction of future CO_2 levels treat the ocean in a very passive way. That is to say, it take up about half of the carbon dioxide that we produce. In fact, it is clearly evident on the basis of observations that the oceans in fact are very sensitive to climate changes, and that there has been evidence in some parts of the oceans that the very processes of removing the CO_2—that is, water mass formation—have in fact ceased and turned on and ceased and turned on in the past. They have been changing by factors of two in many places.

In fact if you think of the oceans as a giant heat engine driven by the contrast in temperature between the Equator and the poles—the Equator as being warm and the poles being cold, and the oceans turning over in response to this temperature difference—most models of temperature increase which we focused on also predict a pronounced warming in the polar regions relative to the equator, so we reduce this thermal contrast. If we reduce this thermal contrast, we reduce the energy of the heat engine and we reduce the oceans' ability to take up the CO_2.

This is a very simplistic argument, but in many respects I think it does hold true. You ask yourself this question: We say by 2100 we may have a factor of 2 increase in the amount of CO_2 in the atmosphere, that is, assuming the oceans take up half of what we put in. What if the oceans take up none? What if they stop? I don't mean stop and stand still in the sense of circulation, but in the sense of the effective processes of removal of CO_2 from the atmosphere.

We have to ask these questions, and I don't think we are in the position of answering them right yet. The major limitation is that we do not have data, we do not have the models, we do not have the computational power to really address and formulate the models that would be necessary to make these predictions. There is a saying in numerical modelers that one good boundary condition is worth 1,000 hours of computer time.

Mr. GORE. I hadn't heard that one before.

Mr. JENKINS. It's certainly true. [Laughter.]

The point being that in fact recent projections have been made that a fully thermodynamic, eddy resolving global circulation model—which is really to say a numerical computer model which is somewhat more realistic, or realistic enough to begin to give us confidence—if it ever existed would take something of the order of 20,000 hours of dedicated CPU time, central processing unit time, on the world's fastest available commercial computer, the CRAY-1 at this stage. That's 3 years of CPU time. There's no indication of bad runs or computer bugs or just the development that would go into that kind of computer model.

So we're faced with constructing very simple-minded models. The models that have been used to take up the CO_2 in these ocean systems are extremely simple. Hopefully we'll improve in the sophistication of these models, but they will not be the utopia of models. That's beyond our wildest dreams, but the more sophisticated the models become, the more we need the data to constrain these models because we're going to take some of these processes which we can't hope to explicitly put into the models and parameterize or average them out.

Unless we really understand what these processes are and we really understand the data and have the confidence in it, we cannot hope to have the models to these systems, and in light of the fact that the oceans as a system will likely change—they have been observed to change during the past climate, as Dr. Broecker has pointed out, and they will likely change in response to the climate that we have been seeing, and even now we see small changes as a result of natural climatic variations—the point is that we need to be able to make these predictions and we can't, and the fundamental limitation is the data.

This is not an engineering problem, as one for the people who decide how these programs are laid out: it's not a problem of taking well-established, fundamental principles, accepted fundamental principles and working them out to the fourth decimal place. This is a problem of understanding the system. The system is very nonlinear. This is a wild force, in a sense, that we are riding, and we need to really understand what's going on there.

Thank you.

Mr. GORE. Well, thank you very much.

Let me try to understand your testimony better, Dr. Jenkins. You're saying that the model of the greenhouse effect that science has been working with and perfecting over the last few years, may have, may include a false assumption about the role of the ocean system in CO_2 absorption. Did you want to——

Mr. JENKINS. I think "false" is, in a sense, an unfair term. I think that it's an expedient, an unrealistic assumption. I think the people who do construct the models realize that the oceans will change.

Mr. GORE. Yes, but because they don't know much about it, they have expediently assumed that it's going to be static, that the rate of CO_2 absorption is probably not going to change very much as atmospheric CO_2 levels increase.

Mr. JENKINS. I think that's a correct statement.

Mr. GORE. Now your studies indicate that actually increased CO_2 levels in the atmosphere may sharply reduce the ability of the oceans to absorb CO_2. Is that correct?

Mr. JENKINS. That's completely feasible, yes.

Mr. GORE. Why?

Mr. JENKINS. Because the processes which remove the carbon dioxide from the atmosphere are those of what are called water mass formation and modification. Basically how the deep ocean works is that you warm waters in the equatorial regions, and warmer waters are lighter, and you cool waters in the polar regions, and cooler waters are heavier. The oceans are stratified: That is to say, the light water lays on the top and the cold water lays on the bottom, and so you rely on this process, or we rely on this process of cooling in the polar regions to remove water from the upper layers into the deeper layers, to take away this carbon dioxide from the atmosphere basically, and that's the major pathway.

Now this process of water mass formation, this cooling in the polar regions, really is driven by the contrast between the Equator and the poles, and if you warm the poles by 5 or 6 degrees Centigrade then you could very well shut off bottom water formation for significant periods of time, decades.

Mr. GORE. Shut off what?

Mr. JENKINS. Shut off bottom water formation, the deep water sinking process that removes this carbon dioxide. Now that's a rather abrupt statement to make, and it's subject to a number of qualifications, but we have seen variations in the rate at which these processes occur.

Mr. GORE. OK. Wait a second. Wait a second. So temperature is what is driving the change in the ocean system behavior, and not CO_2 per se. It's the temperature effect. It's the differential heating at the poles as compared to the Equator.

Mr. JENKINS. Yes. The more——

Mr. GORE. Because the greenhouse effect increases temperature more at the poles than at the Equator, it has a differential effect on the behavior of the oceans in taking warm water that has—in cooling warm water at the poles and sinking it and taking the CO_2 with it down to the bottom. OK? Is that it?

Mr. JENKINS. That's correct.

Mr. GORE. And since the heating up takes place more at the poles than the rate at which that warm water containing CO_2 is submerged, that rate slows down faster than the counterpart at the middle, Equator area where the reverse is taking place. Is that essentially it?

Mr. JENKINS. Yes. In fact, that's one facet of the problem. One which I really did not stress or mention is that in fact you are warming the poles, and if the water is—the water you are trying to sink is not as cold as the water that is already there, you cannot sink it and you cannot remove the carbon dioxide. So in fact it's not just the difference between the Equator and the poles, it's the absolute warming as well that——

Mr. GORE. Yes, yes. I see. Now what does salinity have to do with this?

Mr. JENKINS. Salinity is another component in what is called the equation of state or the determining factors which make water heavier or lighter. In many respects the largest factor in the program or in this aspect is temperature. Salinity does play a role. In general. as oceanographers—and I think you are alluding now to the paper which is at the back of this statement—it is more an indicator of changes that have occurred——

Mr. GORE. Oh, I see.

Mr. JENKINS [continuing]. Rather than the driving force. The alarming thing about this is that we have seen changes in these processes in 5, 10, 15 years, not 100 years but 5 or 10 years, the timeframe which is exactly the one that we are concerned about, the rate at which we are putting CO_2 in. It is entirely possible, for example—observations that have been made in the Labrador Sea, where intermediate waters are formed, waters that sink down to perhaps 1,000 or 2,000 meters, to mid-depths in the ocean, have actually stopped or been reduced to a very small fraction of the normal production rate, if you will—in other words, the rate at which it's sinking—just by natural variations in climate.

Mr. GORE. Yes.

Mr. JENKINS. And so the point is, this really underlines the nonlinear response. If we stop this removal of CO_2, then CO_2 will be sequestered or built up in the atmosphere, and it makes the effect worse. It becomes a vicious circle. So in fact this could be a mechanism very similar to what Dr. Broecker was talking about, where you may switch into a very different mode.

Mr. GORE. Well, now, let me translate all this into its implications. Lots of uncertainties remain, obviously, but the real implication of your work and your analysis is that it's entirely possible for our time frame to be way off, and it is entirely possible for the dire consequences that have been projected to accompany the greenhouse effect, entirely possible for them to occur much sooner than even the most optimistic prior report. Is that——

Mr. JENKINS. Well, I won't take the extreme stand. I'm not an expert in climatology——

Mr. GORE. Yes.

Mr. JENKINS [continuing]. But in oceanography, so I cannot predict, I do not have the qualifications to say what the effects of a sequestering of CO_2 or a buildup of CO_2 in the atmosphere is. But given the spectrum of opinion that does exist—for example, on the one extreme the EPA report, on the other extreme the National Academy report—you can realize that there is some uncertainty as to the magnitude of these effects but that both studies in a sense rely upon the oceans taking up half of the carbon dioxide.

Mr. GORE. Yes.

Mr. JENKINS. And it's entirely possible that the oceans may in some part take up much less than half, and in fact that the CO_2 buildup may be much greater. Now whose predictions will be right within that spectrum of opinion of course is beyond my qualifications, but it certainly says that we should be concerned about this on a more immediate time scale than the next 100 years.

Mr. GORE. Dr. Broecker, did you want to add something to this? You appeared to disagree with the implication I was drawing from Dr. Jenkins' work.

Mr. BROECKER. I guess a bit. I think of the ocean more in terms of the fact that it's connected with the climate system, and that changes in the ocean will ricochet through the system leading to regional changes in climate, rather than of its effect as a CO_2 absorber. Certainly that's important, but I would say my feeling would be that the changes in ocean circulation are unlikely to change the CO_2 uptake by much more than the uncertainty we have in the rate it's going to go in anyway.

I think it just indicates that there is one huge part of this climate system about which we know so little that when we're asked these questions, we really have to hedge an awful lot. We can't really give you the kind of answers you would like to hear. I mean, we have had hundreds and hundreds and hundreds of complete pictures of what the atmosphere is like with regard to wind, with regard to temperature, with regard to all sorts of things. We really have not even one picture of how the deep ocean is and its state, so we're like meteorologists 100 years ago. I mean, it is approaching, I think, that level of difficulty, and we've got a long way to go.

Mr. GORE. I think it was only—what?—2 years ago that they discovered that 98 percent of the kinetic energy in the ocean system was in centrifugal eddies, and previously they had looked at the remaining 2 percent as if it was the entire system.

Dr. Trabalka, did you want to comment on the implications of this possible dramatic lowering in the rate of absorption of CO_2 by the oceans?

Mr. TRABALKA. Only to the extent that I think that what you have heard indicates that the real issue is one of uncertainty about the ocean response. We don't really have any definitive answers at this point, and clearly we do need to get additional information.

Mr. GORE. Mr. McGrath?

Mr. MCGRATH. Mr. Chairman, I ask unanimous consent to insert in the record an opening statement, and I have no questions.

Mr. GORE. Without objection, we will put that in at the beginning of the hearing.

Let me just ask a few more here?

Mrs. SCHNEIDER. What about me?

Mr. GORE. Oh, I'm sorry. Ms. Schneider, I'm sorry. I didn't see you come in.

Mrs. SCHNEIDER. That's all right.

I regret I was detained at another hearing and was unable to hear your prepared testimony. However, I am familiar with at least Dr. Jenkins' and Dr. Broecker's lack of enthusiasm—should I put it politely?—for DOE's approach to the ocean as a part of the climatic system. I happen to serve on two other committees that have jurisdiction over both EPA and NOAA's budgets, and if we are inclined to provide additional funding for those budgets for ocean research, might any of you have some recommendations as to how best to earmark the appropriations of those funds to achieve the goal that you discussed in your testimony?

Mr. BROECKER. Yes, definitely. They should go to the National Science Foundation. I really think so, because most of the work that's being done is being done by university laboratories, and I think that they are used to dealing with the NSF with regard to the complicated logistics of operating ocean programs. What we have seen is that other agencies that are not used to that have difficulty. Of course, you could say—of course, NOAA is not—I suppose that would be my next choice after the National Science Foundation.

Mrs. SCHNEIDER. NOAA?

Mr. BROECKER. I mean, one of the things that I—I realize I am pleased to see that DOE has asked for an increase in their budget in order to accomplish ocean research. One could ask why, when they have $13 million—and the amount that has been asked for by at least the people doing the tracer work that I think everybody agrees is one of the highest things on the agenda, we are asking for about $1 million—why they can't take it out of their present budget. That's one of the things, of course, that bothers me. I don't see why it has to wait for a new appropriation at all.

Mrs. SCHNEIDER. Does anyone else have any comments related to this or anything else that you may not have been asked about? I now offer you that time.

Mr. JENKINS. I would like to append an agreement to what Dr. Broecker has been saying, that NSF is very well suited to the problem in the sense of efficiently administrating a program like this, because they have a long history of dealing with the scientific community as a whole and therefore have an administrative structure already in place, and I think they would be very well suited to administrating this kind of thing.

Ms. SCHNEIDER. OK. Thank you. Yes?

Mr. TRABALKA. I would only comment that at this point in time I believe the oceanographic research community that has been involved in the major ocean measurements program is in the process of an intense reevaluation of that program, and that it may be on the order of a year before we have a really good idea of what the research needs and direction of that program might take.

Mrs. SCHNEIDER. When you say the oceanographic community, it sounds like you're referring to an organized committee or something that's doing this and you have a time frame of 1 year. I am not familiar with specifically what you're referring to.

Mr. TRABALKA. I am specifically referring to the group of scientists that is associated with the Transient Tracers in the Ocean Program, and I believe that Dr. Jenkins is the spokesman for that particular group.

Mrs. SCHNEIDER. And so that's a group made up of scientists from both the Government and the university sectors?

Mr. TRABALKA. Principally, I believe, the university sector.

Mrs. SCHNEIDER. I see. OK, 1 year, 1 year you're looking toward before you come up with recommendations, you're saying?

Mr. TRABALKA. Well, I think Dr. Jenkins ought to be able to comment on that.

Mr. JENKINS. Yes. It's not clear to me that there is a coordinated effort to come up with a specific set of recommendations. We have as a research group—and just a fraction, I think, of the research sector that is involved in this field—been formulating our own research patterns, and the direction of research that we think provides a maximal feedback of information and data that will be required for looking at this kind of problem. There are other programs involved in which, for example, this transient tracers program has been overlapping with. There are two satellite programs that are now being proposed for the early 1990's which we hope to interact with in many respects, but there is no formal study or report that is in the offing in this respect.

Mrs. SCHNEIDER. OK. Thank you.

Thank you, Mr. Chairman.

Mr. GORE. Congressman Volkmer?

Mr. VOLKMER. No questions.

Mr. GORE. Congressman Lewis?

Mr. LEWIS. No questions, Mr. Chairman.

Mr. GORE. Let me ask just a couple more, then.

Dr. Trabalka, your work has shown that the mass of the total carbon pool of the Earth's forests may be as much as 50-percent less than previously supposed, thus reducing the amount of CO_2 that would be produced through deforestation. If this turned out to be the case, could that have a big effect on our understanding of how this works? Specifically, what do you think, in light of that, about the effect of annual deforestation occurring in tropical countries? Is it substantially adding to atmospheric carbon dioxide? We have assumed that it was. Do the implications of your work extend as far as a different answer for that question?

Mr. TRABALKA. The specific point I was making was that the estimate of carbon mass in the tropical forests may be substantially less than formerly indicated, and that may play a major role in our reevaluation of the carbon flux from the tropical forests over the past 30 to 40 years, and indeed the role that they play today in the overall carbon cycle. I believe that this will provide significant information which will be directed toward resolving the current inability to totally balance the carbon cycle.

I think the picture today, say the modern picture of the overall carbon flux from the biosphere, is one of uncertainty. We can't at the present time clearly say that the terrestrial forests are a significant source of CO_2. There is sufficient uncertainty that the forests could be a very small sink or they could be a moderate source or they might be roughly in balance. It's the resolution of that technical issue that we're directed toward.

Mr. GORE. Of course, the annual pattern reflecting the large annual impact of deciduous vegetation in the Northern Hemisphere would indicate that it is a significant sink. Would you agree that the ocean, that the uncertainties surrounding the ocean system probably have more leverage on the outcome of our projections than anything else?

Mr. TRABALKA I suspect that on into the future this may be the case. However, the historical role of the biosphere ultimately is going to provide information on what the role of the ocean is.

Mr. GORE. Very important, too, yes.

Mr. TRABALKA. It's a two-edged sword.

Mr. GORE. Yes.

Mr. TRABALKA. In referring back to your comment about the Mauna Loa record and the "wiggles," the reason you see a fairly symmetrical pattern is believed to be caused by the fact that the biosphere takes out and releases a roughly equal amount of CO_2 every year. There may be an imbalance in the total, but that record alone doesn't really provide any definitive information about the role of the terrestrial biosphere as a source or a sink.

Mr. GORE. Yes; but if it merely reflected the taking out and releasing of an equal amount, it could be a straight line.

Mr. TRABALKA. The timing of the uptake and release is what causes the "wiggles" or the sinusoidal pattern in the record, because it occurs at different seasons of the year.

Mr. GORE. Oh, I thought——

Mr. TRABALKA. During the growing season the biosphere is absorbing net CO_2 from the atmosphere, and then in the fall and later periods the decay of leaves and litter and other materials is then releasing that material back into the atmosphere.

Mr. GORE. OK. Well, I was assuming that it reflected principally the deciduous vegetation in the great land mass of the Northern Hemisphere.

Mr. TRABALKA. That's correct.

Mr. GORE. Dr. Broecker?

Mr. BROECKER. I would like to comment on this. I think that this in a way typifies some of the problems within the CO_2 program. I mean, I may be cutting my own financial throat in saying this because I am involved heavily in this carbon budgeting argument, but I think the field has gotten caught on this point. As I see it, over the last 5 years there has not been much advanced to resolve the problem as to what the role of the forests are, although I won't deny that they're important.

But if we look to the future and ask what are the important questions we have to ask with regard to society, that's not one of the important ones. I think the carbon budget problem is on the firmest ground of all, and there are so many other questions that we should get at. We shouldn't let this one dominate our thinking to the extent that it has been.

Mr. GORE. Looking at that chart again, and I have asked this question before, but I correlated the peaks and the averages on that chart with global fossil fuel consumption as measured by the oil and coal figures, and it may be my imagination, but I'm wondering if any statistical analysis has been done to confirm the correlation with world recessions and world economic recoveries. It certainly appears to reflect the 1974–75 world recession. I mean, it certainly appears to reflect a decline in overall carbon burning. Maybe that's just wrong. Has any statistical analysis been done of that?

Mr. TRABALKA. Statistical analyses have been done for different parts of the record for different purposes. I believe that the one that has been performed via our program most recently suggests very strongly that the correlation with fossil fuels exists and is very real. I believe that probably the period from 1973 on may be perhaps not long enough to do the statistical analysis that we would like to do, to see whether the impact of the Arab oil embargo has indeed been felt in the system.

Mr. GORE. Yes. Well, I just took an overlay of world oil consumption by year and plotted it over that graph and connected the peaks, and it's really a very striking correlation.

Dr. Broecker, you don't buy this?

Mr. BROECKER. No; the flaw in your argument is that the CO_2 is accumulating, and so you are looking at a cumulative curve, and if you look at the actual——

Mr. GORE. But you're looking at a rate of increase. It goes up in any year.

Mr. BROECKER. But the amount of change in the production of CO_2 has been—it has always gone up, except maybe a couple of years it leveled off, so if you looked at the production per year it's almost constant and you wouldn't be able to see it in that.

Mr. GORE. But the consumption, I mean, the burning of it per year is not constant at all, not constant at all.

Mr. BROECKER. Oh, well, the total production of CO_2 was rising, of course, before the Arab boycott in OPEC, by about 4 percent a year. Then at that time the rise leveled off, but now if you look at the total production, of course the total production was going up slowly and then it leveled off.

Well, I was going to get around to what people think those bumps really are. What they think they are is, people that have generated the curve—Keeling and his coworkers—think they have to do with El Nino events, which I wanted to get in before anyway because an El Nino event is one of those curious phenomena that involves an interaction between the atmosphere and ocean that we really don't know dingo about.

Mr. GORE. Yes.

Mr. BROECKER. I mean, we know it happens and we know it has some regularity, but we really don't know the physics of it. I mean, we know something about some parts of the physics but we don't know the overall linkage, and it's thought that those El Nino events influence the amount of CO_2 that is taken up by the ocean or given off by the ocean, so during those events there is a little bit of adjustment. The ocean may give a little CO_2 back to the air or take up a little more than usual.

Mr. GORE. Well, my only point is that in the effort to resolve the uncertainties over the contribution of ocean absorption and the uncertainties over the contribution of deforestation, we also ought to pay attention to the contribution of total fossil fuel consumption, anyway.

Mr. BROECKER. One point: You know, one of the things that has eased the problem, of course, is that we don't have 4 percent growth rate. At 4 percent growth rate you get doubling of CO_2, you know, in the middle of the next century. We now have, what, 1 percent growth rate or less and the projections are small, which pushes the doubling off 50 or 60 years and buys us a fair amount of time.

Mr. GORE. OK. We could ask a lot more questions of this expert panel because you all have got a lot of information we need, but the press of time is going to force us to go to the next panel. We appreciate your contributions here very much. We appreciate the work you're doing. Thank you.

Our next panel is made up of Mr. John Hoffman, Director of the Strategic Studies Staff at EPA; . Thomas Malone, Chairman of the Board of Atmospheric Sciences and Climate for the National Research Council at the National Academy of Sciences, accompanied by John S. Perry, Executive Secretary of the Board of Atmospheric Sciences and Climate; and Rafe Pomerance, president of Friends of the Earth, who is accompanied by Anthony Scoville, who is well known to us, formerly with the Science and Technology staff.

We are delighted to have all of you here. We may need to scoot an extra chair or two up there. I would like to welcome all of you to our hearing and tell you how grateful we are that you have spent the time to help us understand this situation a little bit better. We will hold questions until all three presenters have made their statements. We will begin by saying that, without objection, we will put your prepared statements in the record.

John Hoffman, Director of Strategic Studies at the Environmental Protection Agency, we will begin with you.

STATEMENT OF JOHN HOFFMAN, DIRECTOR, STRATEGIC STUDIES STAFF, U.S. ENVIRONMENTAL PROTECTION AGENCY

Mr. HOFFMAN. I was unable to prepare an opening statement. We didn't have time to clear it with OMB, so if you have some questions that you want to ask——

Mr. GORE. What was OMB's problem.

Mr. HOFFMAN. Well, we just didn't have time to do it. We got the—there was a delay in getting the request from the committee, or rather there was loss of the paper in EPA, so we didn't know about the invitation until Thursday and that doesn't give adequate time to get clearance.

Mr. GORE. Well, can you—I don't know what the failure of communication is. The hearing has been scheduled for quite some time, and I had thought that with both EPA and NAS, we had had staff discussions going back quite some time, but I won't belabor the point. I will just give you the opportunity to present some opening remarks if you would care to.

Mr. HOFFMAN. Well, if you would like me to I can basically tell you what our research focused on. It was really three things. We wanted to look at the question of whether we can delay a greenhouse warming——

Mr. GORE. Could you move the microphone over?

Mr. HOFFMAN [continuing]. Whether we can delay a greenhouse warming by reducing CO_2 emissions, and what we found after our studies was that in the first 60 years in front of us or the next 60 years, that there were no policies, not even a 300-percent tax on fossil fuels worldwide or a coal ban, that would be able to reduce the warming significantly. A 300-percent tax, for example, delayed a 2 degree Centigrade warming about 5 years, from 2040 to 2045, in our studies.

In the second 60 years after that, from 2040 to 2100 on, we found that almost all of the policies could significantly reduce the warming, some of them quite substantially. The reasons for this finding, which might seem surprising at first, really turned out to be threefold. One is, you have a tremendous amount of energy being consumed. A lot of the world's capital is locked into producing and consuming fossil fuels, and even if you have a successful policy it's going to take a long time to get the CO_2 emissions down. Because they accumulate in the atmosphere, CO_2 is going to continue to increase and that is going to add some warming.

The second reason was that there are these other gases, like chlorofluorocarbons 11 and 12, that are used as solvents, refrigerants, methane, nitrous oxides, and a variety of other gases that are increasing, not all of which we considered but the four we did consider contributed about the same amount of warming as CO_2, so obviously a fossil fuel policy is not going to reduce the warming that is associated with those.

Then the third reason we found that these then have a big effect was that there is an unrealized warming that is, when you put CO_2 into the atmosphere it doesn't immediately raise the temperature of the atmosphere the amount that you would expect from the NAS predictions. It has to also raise the temperature of the oceans, as the previous speakers were talking about, and that delays the effect.

Well, this means that there is warming that we haven't experienced from the CO_2 that we put in the atmosphere in the fifties, the sixties, and the seventies along with these other trace gases. You can't stop something that happened in the past. The size of that unrealized warming could be pretty substantial, and I can go into that later, if you want.

Anyway, once we realized that we were going to have this large global warming, the next question you want to ask is, what's the effects? What difference does it make? Who cares? We focused our efforts first on sea level rise, in trying to estimate the amount of sea level rise that might be associated with these temperature increases. There are a lot of uncertainties that are involved in this: the rate of economic growth, fuel prices, technology, how much conservation we have, even the fact that snowfall can fall in the polar areas more as it gets warmer.

We tried to look at all of these uncertainties and we made our best estimates of the amount that the sea level would rise, and we came up with about 1 foot by 2025 and about 3 feet by 2075, which is about the same as what the National Academy came up with in their study that was done by Roger Revell. We also looked at high and low scenarios, where we looked at the worst and best case situations, that is, all optimistic or pessimistic assumptions, and those obviously gave us a much wider band of estimates.

Knowing that the sea level was going to rise, the next question that we wanted to focus our research on was, well, what can we do with this kind of information? What benefit can it have to society? Can it save us money? So we did some studies of sea level rise in Charleston and Galveston in order to look at those questions. As the sea level rises, it is going to erode land. It is going to cause increased flooding during storms, because it starts off the storm waves from a higher level, and it's going to cause salt water to go up rivers and into aquifers, into ground water.

The erosion is going to be a lot more than you would think about from inundation. I mean, a foot of sea level rise on the East Coast is generally going to lead to a retreat of the shoreline on the order of 100 to 200 feet, so you think about it as 1 foot not being very much, but when you push it this way it turns out to be a lot.

Well, we estimated what the damages would be in Charleston without planning, and the damages came out to be pretty high. They were about $1.2 billion. That's present value dollars, discounted. I mean, the dollar in the future we don't count as much as a dollar now.

We wanted to see, then, well, if you built differently, if you built houses in different locations, if you designed the houses differently, if you built sea walls earlier or larger, how much could you reduce these damages? What we found was that in fact you could reduce the damages by about $800 million in Charleston, so you could get a significant savings if people would plan and prepare rather than reacting to these changes. The analysis that we did in Galveston was pretty much the same, that savings were between $250 and $500 million, and we have looked at lots of other projects like wastewater treatment facilities or water intake facilities, and we find that planning ahead can save in those cases, too.

We have done the same kind of analysis in the forest industry, which is an important industry for the country, and there is a place where an opportunity exists because CO_2 makes plants grow faster, but it will make some trees grow faster than other trees. The question is, can the industry pick the trees that will grow fastest and make sure that they are climatically adapted to those areas? What we found was that you could make a difference of about 25 percent in yield if you could pick the right trees. The National Forest Products Association has gotten interested in this, and they are going to have a conference in June to try and help the industry assess just what they need to know to be able to deal with climate change.

The biggest difficulty in doing that kind of analysis that really leads to the issue of the water supply, there is one thing that the foresters have told us, that most of the people that we have been doing these analyses with, that where water will be available, what its seasonality will be, is the critical issue for them. I mean, the sea level rise is actually a relatively small effect, even though it's obviously going to be in the tens of billions of dollars.

Right now it is impossible to really say anything about that because we are unable to predict how water supply will change in different regions of the country, primarily because we don't understand the oceans, as the previous speakers were talking about. If you think about the El Nino, it wasn't caused by CO_2, but just a small change in the surface temperatures of the ocean changed the climate system so dramatically.

Well, if Dr. Broecker is right and you see changes in the climate system altering the circulation and the sea surface temperatures in the future, maybe in abrupt and unexpected ways, we are not going to be able to predict what the—right now we don't have the capability to predict those things, and so we can't predict how water availability will change. That makes it much more difficult if we need to build big projects to bring water into areas, to do it, that is where you have your basic difficulty in continuing these productivity analyses studies.

The question I think from the perspective of policymakers that is most important is how soon do we get this capability? I mean, that's a question that really depends on the kind of research we do and the priority that you people and other people place on this. That is really what is the focus of our research, and we are continuing along those sorts of lines to try and understand what difference it makes in terms of productivity, environmental benefits, and so on.

Mr. GORE. OK. Thank you very much.

Next I would like to call on Dr. Thomas F. Malone, chairman of the Board of Atmospheric Sciences and Climate at the National Research Council over at NAS. We are delighted to have you here, Dr. Malone.

STATEMENT OF DR. THOMAS F. MALONE, CHAIRMAN, BOARD OF ATMOSPHERIC SCIENCES AND CLIMATE, NATIONAL RESEARCH COUNCIL, NATIONAL ACADEMY OF SCIENCES

Mr. MALONE. Thank you, Mr. Chairman.

When you mentioned grandchildren you struck a sympathetic chord. One of the main reasons I am here is because we have 9⅔ grandchildren.

Mr. GORE. Congratulations.

Mr. MALONE. Our report is conservative in its conclusions, and will we hope abate some extreme negative speculations. In brief, we estimate that carbon dioxide will most likely double over the next century. This doubling will result in an increase in average earth temperature between 2 and 8 degrees Fahrenheit, with the lower range most likely. The temperature increase will, in turn, affect sea level, growing seasons, local water supplies, and climate patterns.

Despite the potential seriousness of some of these effects, our committee found the situation to be one of caution, not panic. We recommend expanding monitoring and continued research, but no immediate change in energy policy. One reason for this recommendation is as follows: There are many things we do not understand about CO_2 effects. There are other uncertainties about our future use of fossil and synthetic fuels.

In the committee's own words—and I hope these will stay with your committee, Mr. Chairman—"In our judgment, the knowledge we can gain in coming years should be more beneficial than a lack of action will be damaging. A program of action without a program of learning could be costly and ineffective." I hope that is impressed deeply. Watchwords for the immediate future should, in our committee's view, be research, monitoring, vigilance, and an open mind.

Now, some of the details of our findings. Among the adverse results that have been discussed is a major rise in sea level, about 2 feet over the next 100 years, due to melting of glaciers and expansion of sea water. This rate may increase in following centuries. This is clearly a serious prospect for low-lying areas of the world like Florida, Holland, Bangladesh, but defensive measures seem feasible. A 20-foot rise due to breakup of the West Antarctic ice sheet would take several hundred years, after its surrounding ice shelves had receded. Now to place these changes in context, you might recall that the sea level has risen only about 6 inches in the last century but 500 feet since the last glacial period about 15,000 years ago.

A second potential adverse effect is on agriculture. While predictions of global warming are probably quite reliable, predictions of specific regional climate changes are much less certain. Nevertheless, regional changes will occur and may have serious impacts. Reports of estimates of the aggregate effect on U.S. agriculture through the end of this century indicate that the negative impact of changing climate will be largely balanced by the positive effect of increased fertilization due to increased CO_2. With the demonstrated ability of the U.S. agricultural complex to adapt to changing conditions, yields can be maintained or increased and we predict no overall threat to American agriculture over the next few decades.

I would stress, Mr. Chairman, that the real central issue here is the rate at which the thing called technology per year can increase productivity compared to the rate of change, so we are not taking a big jump of 2 to 8 degrees. It's the yearly change that is the critical factor, and that is often overlooked in impact studies. The most serious effect would be in the arid regions, and even in our own West a slight warming and a decrease of rainfall would, if it occurs, slow stream runoff and could have severe effects.

Now that is the thrust of our report, all 500 pages in a frightening 3 minutes, Mr. Chairman, but I would mention four of what I feel are principal conclusions. The first is that priority attention should be given to long-term options that are not based on combustion of fossil fuels. To be specific, I feel that we should pick up the second generation of the pathbreaking study by Wolfe Haefule at the International Institute of Applied Systems Analysis, where he and his international group thought deeply about how we get from here to there, and that's the kind of thing we should be doing.

Secondly, the evidence at hand does not support steps to change current fuel use from fossil fuels at present; and, third, it is possible—possible—that steps to control costly climatic changes should start with the non-CO_2 greenhouse gases. We need to understand those better. They are looming as increasingly important, and they may be more amenable to control than carbon dixoide.

The fourth conclusion is that this is intrinsically an international problem and requires an international network of science, scientists, convergent with these problems. I stress the importance of achieving a consensus, if possible, within the international scientific community before governments start negotiating how they would cope with this problem. For example, if we were able to develop a photovoltaic method of energy, it could conceivably reduce our demand for coal, which would decrease the price of coal, which would increase the consumption of coal in other countries, so that one country cannot address this problem by itself.

We have in place, and I will be meeting in 2 weeks in Hangzhou, China with a group of scientists, including Chinese, Russian, English, Swedish, to discuss the strategy of a world climate research program. This is a joint enterprise of the International Council of Scientific Unions, the World Meteorological Organization, and the United Nations Environmental Program, and one of the topics is this question of CO_2-induced climatic change, and this is a healthy trend. I met in August with a group in Villach, Austria, looking at the impact. Again, we had representation from these other countries. I will come back to the international in my recommendations.

A few recommendations: Monitoring has loomed large, and I was very impressed with Dr. Broecker's comment in his written testimony about the habitability program of NASA or the geosphere-biosphere program that is being advanced. We will have a symposium in Ottawa in September, bringing together about two dozen scientists from all over the world to discuss a monitoring program which would link together the ocean, the atmosphere, the biosphere, forests, the land, and the solar-terrestrial domain. This is the kind of program that I think would be responsive to the needs expressed earlier this morning.

It is clear to me that the satellite—and again I applaud Dr. Broecker's comment—that the importance of developing the potential of the earth-looking satellite, which has lagged in comparison to astronomical purposes and planetary science purposes, will be a very powerful tool for examining the ocean and for examining the land and the forest. There are major programs: The World Ocean Circulation Experiment, called [WOCE], W-O-C-E; the Tropical Ocean Global Atmosphere with the acronym [TOGA], T-O-G-A, addresses specifically the type of El Nino thing that has been referred to. These are programs just getting underway and they deserve our support.

A second emphasis should be on the non-CO_2 gases. With respect to impact studies, it's clear that the sea level problem and agricultural deserve high priority attention. With respect to emission studies, the kind of models that Dr. Nordhaus developed—and I particularly commend to your attention that chapter in the Academy report written by Dr. Nordhaus, which is a pioneering effort to develop a sound economic emission type of model, and it is also, I believe, supplemented and supported by the work of Edmondson and Reilly at Oak Ridge—these are efforts that should be expanded. We need a larger community, rather than the three or four people that are addressing this now.

The kind of policy studies which have been referred to by Mr. Hoffman—and I am pleased that they started this—I would commend to you the chapter in that report by Mr. Schelling, Professor Schelling, Tom Schelling of Harvard, which analyzes very thoughtfully some of the policy implications.

Finally, I would say two things which are, in part, personal observations from what I have heard this morning. I think that DOE might well institute the kind of peer review program that the National Science Foundation uses to ensure the highest quality in the research it supports, and in conclusion I would plead for a balance among the topics emissions, carbon cycle, climatic change, environment impact, social, economic, and policy considerations.

Thank you, Mr. Chairman.

Mr. GORE. Thank you very much.

We will hold off on questions. I would like to call now on Rafe Pomerance, president of Friends of the Earth, based here in Washington. It's good to have you here.

STATEMENT OF RAFE POMERANCE, PRESIDENT, FRIENDS OF THE EARTH, ACCOMPANIED BY ANTHONY E. SCOVILLE

Mr. POMERANCE. Thank you, Mr. Chairman.

First, let me say a word of congratulations to you. I think that this topic is by far the most important environmental issue that there is. I think it has received too little consideration in the Congress, and I think that your leadership is probably the most important thing in the Congress that has come along on this issue. I have been working on this issue for 7 years, since 1977, and I think that Congress, as an institution, sorely needs to pay much more attention to this problem.

Mr. GORE. Well, thank you very much. I want to make sure the reporter got all that. [Laughter.]

Thank you. Go ahead.

Mr. POMERANCE. I just have to avoid saying "Senator." [Laughter.]

Mr. GORE. We'll have equal time, equal time.

Mr. POMERANCE. Just a word about my own work on this. I worked on the Clean Air Act for many years in the midseventies, and after that did a good deal of reading on the CO_2 problem, and was named a member of the CO_2 Advisory Committee of the Department of Energy in the late seventies. The committee stopped meeting in the eighties. It was never disbanded, to my knowledge, but I always found the discussions were—I think I was the only person with a bachelor's degree in that forum—it was rather intimidating but very fascinating, because we debated and discussed all the most important issues, or at least the ones that people thought of at the time. I think it was unfortunate, but——

Mr. GORE. Are you saying the others were high school dropouts? [Laughter.]

Mr. POMERANCE. I figured that was coming.

Mr. GORE. Go ahead.

Mr. POMERANCE. Let me say a word, just in contrast to most of what has been said this morning. I think it is time to act. In fact, it's really too late to avoid, or it appears, initial warming. We know what to do. The evidence is in. The problem is as serious as exists. People talk about not leaving this to their grandchildren. I'm concerned about leaving this to my children.

When we were working on the problem in the early seventies, you can see there has been a big bump just since the late seventies until now. The longer we wait, the more trouble we're going to be in, and this morning's testimony I will say did not leave me any easier with the notion that the oceans all of a sudden might change their takeup of CO_2. I believe this is a legacy we cannot leave to future generations. We have a fairly benign climate globally, and I don't think we should put it at risk.

The research budget on this issue is far too little. DOE has $13 million, and we know that $13 million is not very much money in terms of what Federal research dollars are pushed around. I feel that anything that the scientific community requests, just about, should be granted. I am not a scientist; I have no self-interest in that, but it is ridiculous to be spending such small sums of money on one of the most formidable problems that civilization faces.

A comment on the scientific community: Having listened to many of these hearings over the years, my conclusion is that we will never or virtually never hear from the scientific community in terms of telling you Members of Congress to act. You are the ones who are going to have to make that decision. Don't rely on the scientists. It's not their job. They're not going to tell you. They're going to say, "It's not my arena."

The wait-and-see point of view as elaborated by the NAS in my mind is absolutely wrong. It's too cautious. The EPA, on the other hand, whose report I thought was a major breakthrough in terms of addressing all the policy issues at once, I thought missed the mark because they basically implied there was nothing to do, it was too late. The NAS said we can wait and see. Well, if you take the testimony you have heard this morning that people, even Carl Sagan and Wally Broecker, are saying that 1 degree is big enough to make major changes, we may already in fact be committed to 1 degree, so why wait?

Those are a few observations. I would just like to turn to our recommendations here and read those. This is the conclusion of our views, that some climatic change from fossil energy use, industrial pollution, and agricultural practices will occur. We urge prompt efforts to plan for adaption to these changes in low-lying areas. We support immediate funding for a large-scale global research program on ocean circulation. We understand that some consideration is being given to a joint EPA/NSF/NASA effort under the latter's proposed global habitability project, utilizing the space shuttle. As demonstrated by the recent El Nino effects, this research would be of great practical importance, far beyond the analysis of CO_2-caused climate warming.

We urge that energy efficiency and energy conservation become the top goal of U.S. domestic and foreign energy policies, in order to prevent the severe climatic changes that will occur if average world temperatures rise 4 degrees above current levels. Energy companies, and especially electric utilities, should be mandated to invest in energy conservation first and conventional energy production only second when applying for certificates of public need.

In this connection, we recommend abolishing the Synthetic Fuels Corporation and reappropriating funds to speed implementation of energy conservation and efficiency at the Federal, State, and local levels. Greatly increased research and development funds should be allocated to solar and renewable energy, including biomass.

Policies to ameliorate world climate change also facilitate solutions to other environmental problems, such as acid rain, while providing economically efficient energy investments and promoting energy security. Especially we recommend consolidation of research and development in this area to bring about more rapid policy change. We also urge immediate and large increases in research to study trace greenhouse gases other than CO_2.

U.S. support for conservation and renewable energy sources will stimulate greater acceptance of these resources by developing nations just when their energy use is expected to begin making a serious contribution to world CO_2 and trace greenhouse gas emissions. We urge that the recommitment of CO_2 climate change and other geochemical cycling efforts be incorporated as criteria for U.S. support of international development projects as well as our international science and technology policies.

We must act now to forestall serious climatic change beyond what we are already committed to. The United States bears a special responsibility as the world's largest user of fossil energy and the Nation with the world's second largest coal reserves. We should not continue man's experiment with world climate until we have a far better understanding of what the results will be. Today we do not know the consequences. Once we do, they will be irreversible for centuries. Furthermore, policies to limit climate change make the best dollars and sense.

Thank you.

[The prepared statement of Mr. Pomerance follows:]

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FRIENDS OF THE EARTH

530 7TH STREET, S.E., WASHINGTON, D.C. 20003
(202) 543-4312

TESTIMONY SUBMITTED BY
RAFE POMERANCE, PRESIDENT
FRIENDS OF THE EARTH

TO
THE SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURAL RESEARCH AND ENVIRONMENT
AND
THE SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT
OF
THE COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

CARBON DIOXIDE AND THE GREENHOUSE EFFECT

FEBRUARY 28, 1984

Committed to the preservation, restoration, and rational use of the ecosphere

Mr. Chairman, Friends of the Earth is an international environmental organization with 30,000 members in the United States and affiliates in 22 nations. We commend you for holding this hearing on carbon dioxide, the greenhouse effect, and world climate change. Save for nuclear war, no environmental risk is greater than climate change caused by burning fossil fuels, by industrial pollutants, by deforestation, and by agricultural exploitation propelled by world population and economic pressure.

Two years ago, in March 1982, Friends of the Earth testified to these Subcommittees that your "hearing comes at a critical time when evidence is accumulating that climate change could be one of the most serious and irreversible effects of accelerating fossil energy use." Since that time, Mr. Chairman, the Environmental Protection Agency (EPA), and the National Academy of Sciences (NAS) released independent studies on the "greenhouse effect"-- the warming of the atmosphere caused by the release of carbon dioxide (CO_2) from burning coal, oil, and natural gas, as well as tropical deforestation, and industrial emissions of other trace "greenhouse" gases. EPA foresees a rise in atmospheric temperatures as early as the 1990's reaching major proportions early in the next century. The NAS puts the date for significant climate change in the mid-twenty-first century.

This atmospheric warming could easily bring us a climate averaging 4°C warmer than today but the warming would be three to five times greater in polar regions. These increasing average temperatures together with reduced temperature differences between the equator and arctic regions will brirg large shifts in rainfall patterns. Paleoclimate evidence as well as the 1930's dustbowl indicate that the American wheat and corn belt, which supply most of the world's grain exports, might experience devastating drought for a long time, up to 1000 years. Thermal expansion of ocean water, similar to the rise of mercury in a thermometer, has already been observed and could cause serious erosion of beaches and coastal land if atmospheric warming continues as expected. These effects would be amplified over a longer time by melting of Arctic Ocean ice as well as alpine glaciers, and the Greenland and West Antarctic ice sheets.

In an overcrowded, overarmed world, the disruption of food supplies, or the loss of crop and coastal lands could well lead to widespread wars including the strong possibility of accidental superpower conflict when climate change reinforces other pressures on natural resources. In the final analysis the latter risk is probably the greatest danger of world climate change. While it may be possible, though probably not desirable, to adapt to some cliimate change, history suggests that such transitions are often accompanied by conflict-- a global disaster in the nuclear era if superpowers were involved as would be highly probable.

When it comes to recommendations, the two reports draw opposite conclusions. The Environmental Protection Agency says it is too late to stop global warming and that the best policy is to adapt. The National Academy of Sciences concludes that we do not yet know what to do. It recommends waiting while further studies are conducted. The truth is neither. We must prepare for some climate change while also acting NOW to prevent dractic climate modification which will result if current energy, industrial and agricultural policies continue.

The NAS's recommendation is indeed surprising. One of the pioneering experts, who warned about the greenhouse effect as long ago as 1957 and who was Chairman of the Academy's panel which produced its 1977 report, Energy and Climate, Roger Revelle has testified to this committee that, "in adding CO2 to the atmosphere, mankind is unintentionally conducting a great experiment" involving the entire world--all people, all life.

Because of the heat storage of the oceans, the effects of carbon dioxide and other greenhouse gases only appear after a long delay. Once a detectable warming occurs, no measure can stop serious climate disruptions. Even now the latest evidence indicates that we are locked into a 1°C global warming if we never burned another gallon of oil or another ton of coal. That rise alone will be warmer than anytime in the last 1000 years. Further, given the 50 year period historically required to change a nations's primary fuel, it is quite possible in practice that we will not stop the global warming before it reaches 2°C if other trace greenhouse gases, as well as CO2, continue to increase. A 2°C warming would raise the average world temperature to the highest it has been in 125,000 years.

Continuation of present patterns of fossil fuel consumption, especially if coal replaces oil, have been projected by scientists to lead to a global temperature increase of 4°C or more.

Surely no responsible scientist would conduct an experiment with such enormous consequences without being reasonably certain of the outcome. Yet, although the National Academy acknowledges great uncertainties in this "unintentional experiment", it fails to recommend cancelling the experiment until we have more information.

We *should* conclude just the opposite. While there are many uncertanties particularly related to ocean circulation, the general scientific evidence on the strength of the greenhouse effect has been verified to within 2°C for three planets: Venus, Mars, and Earth. There is no doubt about the Greenhouse Effect; there is no doubt that atmospheric CO2 in increasing; the only question is what will be the precise effects of the final 2°C temperature change. In view of the conflicting pressures of the political arena, that final increment of scientific certainty will not suddenly rally the world's decision-makers.

The burden of proof of safety falls on those who propose continuing present energy and agricultural policies until "all the evidence is in". By then it will be too late to cancel the experiment. We must act now to reduce the use of fossil fuels until we know what the results will be, not *vice versa*. Of course, that policy would serve many other ends such as reducing acid rain, increasing energy security, and promoting the development of energy conservation, as well as solar and renewable energy for the future--when oil is scarce.

Contrary to EPA's initial assessment, there is hope. We can at least avoid a major greenhouse effect even if some climatic change is in the works. Catastrophic warming is neither an act of God, nor man's fate because determinate economic models tell us so. Rather, it is a direct result of energy, population, agricultural, and industrial policies. We need to implement energy and population policies that will reduce world fossil fuel consumption. And we must stop the pollution produced by manufacturing and industrial agriculture, which is the source of other trace greenhouse gases, such as freons, methane, nitrous oxide, and ozone. Some of these gases are already known to cause over $2 billion in crop losses annually and could themselves drive a substantial climate warming even if we drastically reduce fossil energy use. Much more research must be funded to discover the sources and potential danger of these trace gas emissions.

In its projections of future fuel needs, EPA assumes that an extra dollar of income on industrial production will create a unit of energy demand in a lockstep. For example, the study projects that through the growth of per capita GNP, Americans will consume 325% as much food, clothing, housing, motor vehicles, and similar products in 2050 as today. That projection is more a Dow-Jones forecast of health spa stocks than an accurate measure of our nation's girth! It overlooks the effect of consumer saturation (do we really need three cars per person?), reduced working hours, and structural shifts from a predominantly industrial to an information-intensive economy.

EPA also assumes the Western style development of the Third World. For example, Africa would have a per capita annual income of $1940 in 2050 as opposed to $340 in 1975. Natural resource limitations make such growth extremely unlikely. Clearly, while economies will grow, increases in the standard of living must come primarily in the quality, not quantity, of life-- for many reasons, of which climatic change, as well as the depletion of soil and other natural resources are but partial constraints.

For the early twenty-first century, at which time we could now significantly affect energy supply and demand over the whole economy, there are a wealth of new money saving high efficiency technologies using a fraction of the energy we consume today. Many recent studies, including the Solar Energy Research Institute's (SERI) "Sawhill" study have found that we can substantially reduce energy consumption even while the economy keeps growing.

For example, in the U.S., Canada, and Europe, contractors are now building houses that consume only 5-10% of the average heating energy used today. In Canada there are "zero-energy" office buildings which live off the heat produced by their lighting, by heat produced by office equipment, and the body heat of their occupants. Car manufacturers have demonstrated 80-100 mile per gallon versions of existing subcompacts. At 80 mpg, during their lifetime, these cars would save 5,300 gallons of gasoline and approximately $6,600 against the typical car on the road today which averages 15.3 miles per gallon. That represents an 80% reduction in CO_2 emissions and a corresponding increase in energy efficiency. For all classes of vehicles, conversion t high energy efficiency would bring major savings to consumers.

Similar progress has been made in the development of renewable energy. Here the U.S. is in a leading position to open potential worldwide markets for its industry.

Together, high efficiency and renewable energy offer the opportunity to reduce fossil fuel consumption to a fraction of today's level. The possibilities have been set forth in detail by my colleagues, Amory and Hunter Lovins, Florentin Krause, and Wilfred Bach in their report commissioned by the West German government, and published in the U.S. as Least Cost Energy, as well as other publications of the International Soft Energy Project. These two strategies could delay further atmospheric changes enough to safely conduct a hundred years of research on the greenhouse effect while we develop the political and economic institutions to responsibly exercise climatic stewardship in the twenty-first century-- sixteen years from now. In that case, climate change would be largely confined to the limited warming that will occur if all CO_2 emissions ceased tommorrow.

But the new generation of energy technologies will only be in place on time if public and financial policies mobilize the necessary research and capital so that consumers will use them.

We need to motivate appliance, automobile, and equipment manufacturers to produce high efficiency products beginning now. Consumers will only pay the higher capital costs if they understand their economic interest in doing so and if it is easy to purchase, pay and service these technological improvements. One model is that of electrical utilities which promote and finance money-saving energy conservation. But even California, which has been a leader, has a long way to go. For example, it would pay California electrical utilities to give a free high efficiency refrigerator to every family in the state while saving the need to construct 1700 megawatts of generating capacity. In the Midwest a similar strategy could help to solve the acid rain problem by reducing the need for stack scrubbers while also limiting CO_2 emissions.

For the most part, implementation of this climate-saving strategy can rely on market competition. Internationally, as Harvard Business School's energy experts, Robert Stobaugh and Daniel Yergin have pointed out, the United States exercises a strong market demand pull once the momentum for conservation and renewable energy is established. Such leadership is all the more important since developing nations' energy consumption is now strongly shaped by the products and technologies provided by industrial nations.

On the average over the next five decades, industrial nations could have the same standard of living while using about 20% of the energy per person that we use today. And we could save money. As noted earlier, investing in these improvements is far cheaper than building new power stations and synthetic fuel plants. We should support redirecting money appropriated for the Synfuels pork barrel to local, regional and Federal programs for energy conservation and renewable sources.

Unfortunately, the Reagan administration has dismantled or attacked every Federal energy program in the area of solar and conservation. For FY 1985, the request for research on CO2 stands at $13 million or $3 million below the $16 million requested by President Reagan in his initial budget for FY 1982. Federal energy policies must be reversed. If we are incapable of doing so now when it would pay to do so and would provide greater long term energy security, can we hope to mobilize the discipline and sacrifice demanded without conflict in a world inundated by unprecedented climatic changes?

In sum, Mr. Chairman, Friends of the Earth concludes:

1. That some climatic change from fossil energy use, industrial pollution, and agricultural practices will occur. We urge prompt efforts to plan for adaptation to these changes in low lying states such as Florida and low lying countries such as Bangladesh.

2. We support immediate funding for a large-scale global research program on ocean circulation. We understand that some consideration is being given to a joint EPA, NSF, NASA effort under the latter's proposed global habitability

project utilizing the space shuttle. As demonstrated by recent "El Nino" effects, this research would be of great practical importance far beyond the analysis of CO2-caused climate warning.

3. We urge that energy conservation become the top goal of U.S. domestic and foreign energy policies in order to prevent the severe climate changes which will occur if average world temperatures rise 4°C above current levels. Energy companies, and especially electrical utilities, should be mandated to invest in energy conservation first and conventional energy production only second when applying for certificates of public need. In this connection we recommend reappropriating funds for the Synthetic Fuels Corporation to speed implementation of energy conservation at the Federal, state and local levels. Greatly increased research and development funds should be allocated to solar and renewable energy resources, including biomass.

4. Policies to ameliorate world climate change also facilitate solutions to other environmental problems such as acid rain, while providing economically efficient energy investments and promoting energy security. Especially we recommend consolidation of all research and development related to environmental problems arising from man's influence a global energy and geochemical cycles. We also urge immediate and large increases in research to study

trace greenhouse gases other than CO_2.

5. U.S. support for energy conservation and renewable energy sources will stimulate greater acceptance of these resources by developing nations just when their energy use is expected to begin making a serious contribution to world CO_2 and trace greenhouse gas emissions. We urge that consideration of CO_2 climate change and other geochemical cycling effects be incorporated as criteria for the U.S. support of international development projects as well as our international science and technology policies.

6. We must act now to forestall serious climatic change beyond what we are already committed to. The United States bears a special responsibility as the world's largest user of fossil energy and as the nation with the world's second largest coal reserves. We should NOT continue man's experiment with world climate until we have a far better understanding of what the results will be. Today we do not know the consequences. Once we do, they will be irreversible for several centuries. Furthermore, policies to limit climate change make the best dollars and sense.

Thank you, Mr. Chairman.

Mr. Rafe Pomerance is President of Friends of the Earth and a member of the Department of Energy's Advisory Board on CO_2. The Board has not been convened in three years.

** In preparation of this testimony Mr. Pomerance was assisted by Dr. Florentin Krause and Anthony Ellsworth Scoville.

Dr. Florentin Krause is co-director of the International Project for Soft Energy Paths of Friends of the Earth and a co-author of *Least-Cost Energy: Solving the CO_2 Problem*.

Anthony Ellsworth Scoville was a Science Consultant to the U.S. House of Representatives Committee on Science and Technology from 1977-1981. He is currently writing a book for Friends of the Earth about man's impact on climate and its relationship to industrial innovation policy.

Mr. POMERANCE. I would ask that Mr. Scoville, my associate, be given a minute to talk about one important—if you would grant it.

Mr. GORE. Sure. Go ahead.

Mr. SCOVILLE. Thank you, Mr. Chairman.

On page 3 of our testimony we make the comment that we appear to be locked into a 1 degree Centigrade global warming, even if we never burned another gallon of oil or another ton of coal. That's a fairly controversial statement, and for the benefit of the committee I would just like to justify where that is coming.

It is based on a discussion I had yesterday with Dr. James Hansen of the Goddard Institute for Space Studies in New York, who is one of the pioneering researchers in this area——

Mr. GORE. He testified before an earlier hearing we had on this.

Mr. SCOVILLE. Anyhow, last year he gave a paper to the Ewing Symposium at the Lamont-Doherty Geological Institute, and it is going to be published this April by the American Geophysical Union. Now what he says is that his work essentially predicts a substantially larger climate change for a doubling of CO_2 than is predicted or expected at least by the McCracken paper in the National Academy of Science report, and is also cited by the Department of Energy testimony which will be presented shortly—but I have seen the written text here.

When I asked him for an explanation of this, what he said is that the critical difference is that the National Academy study assumes that the thermal response time of the ocean to a CO_2 change is, in effect, a physical constant of 15 years. In fact, what he told me yesterday is that there is an interrelationship between the sensitivity of the atmosphere to a CO_2 rise and to the length of the thermal response of the oceans. What this basically says is that the more sensitive the atmosphere is to a climate change, to a rise in CO_2, the longer it will take for that observable temperature to actually turn up in our records.

What Dr. Hansen's work appears to suggest is that there may be a serious technical flaw—it's not an error, because it's just a question not yet fully understood—in the NAS's calculations and in corresponding Department of Energy expectations for the average climate temperature rise of between 1.5 and 3 degrees Centigrade, as given in the DOE testimony. So what Dr. Hansen says is that, based upon his latest paper which I will be glad to supply to the committee as soon as I receive it from him, that we are essentially—if we include the non-CO_2 trace greenhouse gases together with the CO_2 buildup that has already occurred and we match that with the most recent estimates of the lowered preindustrial level of CO_2—that we appear to have already essentially committed ourselves to a climate change of 1 degree Centigrade, but only a very small fraction of that has been observed today.

Anyhow, as I say, Dr. Hansen did say that he would be glad if I wanted to quote my conversation with him yesterday, and I would be glad to make a copy of the paper available to you as soon as it arrives.

[Material follows:]

CLIMATE SENSITIVITY: ANALYSIS OF FEEDBACK MECHANISMS*

J. Hansen, A. Lacis, D. Rind, G. Russell

NASA/Goddard Space Flight Center, Institute for Space Studies
2880 Broadway, New York, NY 10025

P. Stone

Center for Meteorology and Physical Oceanography
Massachusetts Institute of Technology, Cambridge, MA 02139

I. Fung

Lamont-Doherty Geological Observatory of Columbia University
Palisades, NY 10964

R. Ruedy, J. Lerner

M/A COM Sigma Data, Inc.
2880 Broadway, New York, NY 10025

Abstract. We study climate sensitivity and feedback processes in three independent ways: (1) by using a three dimensional (3-D) global climate model for experiments in which solar irradiance S_0 is increased 2 percent or CO_2 is doubled, (2) by using the CLIMAP climate boundary conditions to analyze the contributions of different physical processes to the cooling of the last ice age (18K years ago), and (3) by using estimated changes in global temperature and the abundance of atmospheric greenhouse gases to deduce an empirical climate sensitivity for the period 1850-1980.

Our 3-D global climate model yields a warming of ~4°C for either a 2 percent increase of S_0 or doubled CO_2. This indicates a net feedback factor of f = 3-4, because either of these forcings would cause the earth's surface temperature to warm 1.2-1.3°C to restore radiative balance with space, if other factors remained unchanged. Principal positive feedback processes in the model are changes in atmospheric water vapor, clouds and snow/ice cover. Feedback factors calculated for these processes, with atmospheric dynamical feedbacks implicitly incorporated, are respectively $f_{water\ vapor} \sim 1.6$, $f_{clouds} \sim 1.3$ and $f_{snow/ice} \sim 1.1$, with the latter mainly caused by sea ice changes. A number of potential feedbacks, such as land ice cover, vegetation cover and ocean heat transport were held fixed in these experiments.

We calculate land ice, sea ice and vegetation feedbacks for the 18K climate to be $f_{land\ ice} \sim 1.2$-1.3, $f_{sea\ ice} \sim 1.2$, and $f_{vegetation} \sim 1.05$-1.1 from their effect on the radiation budget at the top of the atmosphere. This sea ice feedback at 18K is consistent with the smaller $f_{snow/ice} \sim 1.1$ in the S_0 and CO_2 experiments, which applied to a warmer earth with less sea ice. We also obtain an empirical estimate of f = 2-4 for the fast feedback processes (water vapor, clouds, sea ice) operating on 10-100 year time scales by comparing the cooling due to slow or specified changes (land ice, CO_2, vegetation) to the total cooling at 18K.

The temperature increase believed to have occurred in the past 130 years (approximately 0.5°C) is also found to imply a climate sensitivity of 2.5-5°C for doubled CO_2 (f = 2-4), if (1) the temperature increase is due to the added greenhouse gases, (2) the 1850 CO_2 abundance was 270±10 ppm, and (3) the heat perturbation is mixed like a passive tracer in the ocean with vertical mixing coefficient $k \sim 1\ cm^2\ s^{-1}$.

These analyses indicate that f is substantially greater than unity on all time scales. Our best estimate for the current climate due to processes operating on the 10-100 year time scale is f = 2-4, corresponding to a climate sensitivity of 2.5-5°C for doubled CO_2. The physical process contributing the greatest uncertainty to f on this time scale appears to be the cloud feedback.

We show that the ocean's thermal relaxation time depends strongly on f. The e-folding time constant for response of the isolated ocean mixed layer is about 15 years, for the estimated value of f. This time is sufficiently long to allow substantial heat exchange between the mixed layer and deeper layers. For f = 3-4 the response time of the surface temperature to a heating perturbation is of order 100 years, if the perturbation is sufficiently small that it does not alter the rate of heat exchange with the deeper ocean.

The climate sensitivity we have inferred is larger than that stated in the Carbon Dioxide Assessment Committee report (CDAC, 1983).

*To appear in Climate Processes and Climate Sensitivity, (Maurice Ewing Series, 5, editors J.E. Hansen and T. Takahashi), American Geophysical Union, Washington, D.C., 368 pp., April, 1984

Their result is based on the empirical temperature increase in the past 130 years, but their analysis did not account for <u>the dependence of the ocean response time on climate sensitivity.</u> Their choice of a fixed 15 year response time biased their result to low sensitivities.

We infer that, because of recent increases in atmospheric CO_2 and trace gases, there is a large, rapidly growing gap between current climate and the equilibrium climate for current atmospheric composition. Based on the climate sensitivity we have estimated, the amount of greenhouse gases <u>presently in the atmosphere</u> will cause an eventual global mean warming of about 1°C, making the global temperature at least comparable to that of the Altithermal, the warmest period in the past 100,000 years. Projection of future climate trends on the 10-100 year time scale depends crucially upon improved understanding of ocean dynamics, particularly upon how ocean mixing will respond to climate change at the ocean surface.

Introduction

Over a sufficient length of time, discussed below, thermal radiation from the earth must balance absorbed solar radiation. This energy balance requirement defines the effective radiating temperature of the earth, T_e, from

$$\pi R^2(1 - A)S_0 = 4\pi R^2\sigma T_e^4 \qquad (1)$$

or

$$T_e = [S_0(1 - A)/4\sigma]^{1/4} = (a/\sigma)^{1/4} \qquad (2)$$

where R is the earth radius, A the earth albedo, S_0 the solar irradiance, a the mean flux of absorbed solar radiation per unit area and σ the Stefan-Boltzmann constant. Since $A \sim 0.3$ and $S_0 \sim 1367$ W m^{-2}, $a \sim 239$ W m^{-2} and this requirement of energy balance yields $T_e \sim 255$K. The effective radiating temperature is also the physical temperature at an appropriately defined mean level of emission to space. In the earth's atmosphere this mean level of emission to space is at altitude $H \sim 6$ km. Since the mean tropospheric temperature gradient is ~5.5°C km^{-1}, the surface temperature is $T \sim 288$K, ~33K warmer than T_e.

It is apparent from (2) that for changes of solar irradiance

$$\frac{dT_e}{T_e} = \frac{1}{4}\frac{dS_0}{S_0} = \frac{1}{4}\frac{da}{a} \qquad (3)$$

Thus if S_0 increases by a small percentage δ, T_e increases by $\delta/4$. For example, a 2 percent change in solar irradiance would change T_e by about 0.5 percent, or 1.2-1.3°C. If the atmospheric temperature structure and all other factors remained fixed, the surface temperature would increase by the same amount as T_e. Of course all factors are not fixed, and we therefore define the net feedback factor, f, by

$$\Delta T_{eq} = f\,\Delta T_0 \qquad (4)$$

where ΔT_{eq} is the equilibrium change of global mean surface air temperature and ΔT_0 is the change of surface temperature that would be required to restore radiative equilibrium if no feedbacks occurred.

We use procedures and terminology of feedback studies in electronics (Bode, 1945) to help analyze the contributions of different feedback processes. We define the system gain as the ratio of the net feedback portion of the temperature change to the total temperature change

$$g = \frac{\Delta T_{feedbacks}}{\Delta T_{eq}} \qquad (5)$$

Since

$$\Delta T_{eq} = \Delta T_0 + \Delta T_{feedbacks}, \qquad (6)$$

it follows that the relation between the feedback factor and gain is

$$f = \frac{1}{1 - g} \qquad (7)$$

In general a number of physical processes contribute to f, and it is common to associate a feedback factor f_i with a given process i, where f_i is the feedback factor which would exist if all other feedbacks were inoperative. If it is assumed that the feedbacks are independent, feedback contributions to the temperature change can be separated into portions identifiable with individual feedbacks,

$$\Delta T_{feedbacks} = \sum_i \Delta T_i, \qquad (8)$$

with

$$g = \sum_i \frac{\Delta T_i}{\Delta T_{eq}} = \sum_i g_i \qquad (9)$$

and

$$\Delta T_{eq} = \frac{1}{1 - \sum_i g_i}\,\Delta T_0 \qquad (10)$$

It follows that two feedback gains combine linearly as

$$g = g_1 + g_2 \qquad (11)$$

but the feedback <u>factors</u> combine as

$$f = \frac{f_1 f_2}{f_1 + f_2 - f_1 f_2} \qquad (12)$$

Thus even when feedback processes are linear and independent, the feedback factors are not multiplicative. For example, a feedback process with gain $g_i = 1/3$ operating by itself would cause a 50 percent increase in ΔT_{eq} compared to the no feedback radiative response, i.e., $f_i = 1.5$. If a second feedback process of the same strength is also operating, the net feedback is $f = 3$ (not 2.25). One implication is that, if strong positive feedback exists, a moderate additional positive feedback may cause a large increase in the net feedback factor and thus in climate sensitivity.

The feedback factor f provides an intuitive quantification of the strength of feedbacks and a convenient way to describe the effect of feedbacks on the transient climate response. The gain g allows clear comparison of the contributions of different mechanisms to total climate change. The above formalism relates f and g and provides a framework for analyzing feedback interactions and climate sensitivity.

A number of physical mechanisms have been identified as causing significant climate feedback (Kellogg and Schneider, 1974). As examples, we mention two of these mechanisms here. Water vapor feedback arises from the ability of the atmosphere to hold more water vapor as temperature increases. The added water vapor increases the infrared opacity of the atmosphere, raising the mean level of infrared emission to space to greater altitude, where it is colder. Because the planetary radiation to space temporarily does not balance absorbed solar energy, the planet must warm to restore energy balance; thus $f_w > 1$ and $g_w > 0$, a condition described as a positive feedback. Ice/snow feedback is also positive; it operates by increasing the amount of solar energy absorbed by the planet as ice melts.

Feedback analyses will be most useful if the feedback factors are independent to first order of the nature of the radiative forcing (at the top of the atmosphere). The similar model responses we obtain in our S_0 and CO_2 experiments tend to corroborate this possibility, although there are some significant differences in the feedbacks for solar and CO_2 forcings. We expect the strength of feedbacks to have some dependence on the initial climate state and thus on the magnitude of the climate forcing; for example, the ice/snow albedo feedback is expected to change with climate as the cryospheric region grows or shrinks.

We examine feedback processes quantitatively in the following sections by means of 3-D climate model simulations and analysis of conditions during the last ice age (18K years ago). The 3-D experiments include doubling CO_2 and increasing S_0 by 2 percent, forcings of roughly equal magnitude which have also been employed by Manabe and Wetherald (1975) and Wetherald and Manabe (1975). 18K simulations with a 3-D general circulation model have previously been performed by Williams et al. (1974), Gates (1976) and Manabe and Hahn (1977).

Three-Dimensional Climate Model

The global climate model we employ is described and its abilities and limitations for simulating today's climate are documented as model II (Hansen et al., 1983b, hereafter referred to as paper 1). We note here only that the model solves the simultaneous equations for conservation of energy, momentum, mass and water and the equation of state on a coarse grid with horizontal resolution 8° latitude by 10° longitude and with 9 atmospheric layers. The radiation includes the radiatively significant atmospheric gases, aerosols and cloud particles. Cloud cover and height are computed. The diurnal and seasonal cycles are included. The ground hydrology and surface albedo depend upon the local vegetation. Snow depth is computed and snow albedo includes effects of snow age and masking by vegetation.

Ocean temperatures and ice cover are specified climatologically in the documented model II. In the experiments described here, ocean temperatures and ice cover are computed based on energy exchange with the atmosphere, ocean heat transport, and the ocean mixed layer heat capacity. The latter two are specified, but vary seasonally at each gridpoint. Monthly mixed layer depths are climatological, compiled from NODC mechanical bathythermograph data (NOAA, 1974) and from temperature and salinity profiles in the southern ocean (Gordon, 1982). The resulting global-mean seasonal-maximum mixed layer depth is 110m. In our 3-D experiments a 65m maximum is imposed on the mixed layer depth to minimize computer time; this yields a global-mean seasonal-maximum mixed layer depth of 63m. The 65m maximum depth is sufficient to make the mixed layer thermal response time much greater than one year and provide a realistic representation of seasonal temperature variations, so the mixed layer depth limitation should not significantly affect the modeled equilibrium climate.

The ocean heat transport was obtained from the divergence of heat implied by energy conservation at each ocean gridpoint in the documented model II (paper 1), using the specified mixed layer depths. The geographical distribution of the resulting annual mean heat flux into and out of the ocean surface is shown in Fig. 1a; averaged over the entire hemispheres, it yields 2.4 W m^{-2} into the Southern Hemisphere surface and an equal amount out of the Northern Hemisphere. The gross characteristics of the ocean surface heating and implied ocean heat transport appear to be realistic, with heat input at low latitudes, especially in regions of upwelling cold water, and release at high latitudes, especially in regions of poleward currents. Fig. 15 of paper 1 shows that the longitude-integrated heat transport is consistent with available knowledge of actual transports. A more comprehensive comparison with observations

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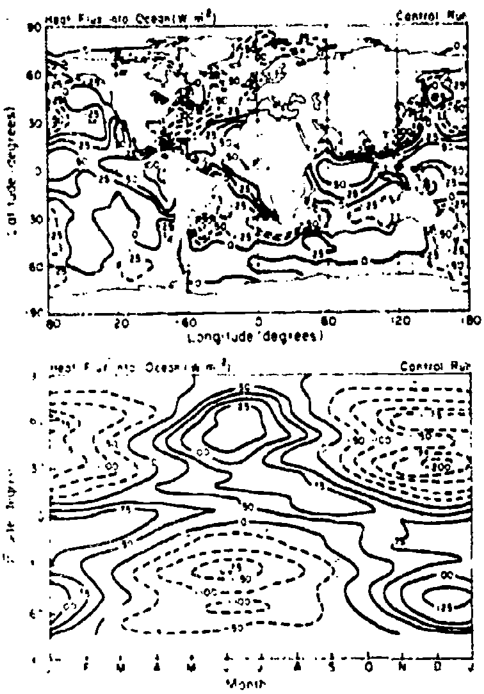

Fig. 1. Specified heat flux into the ocean surface in the 3-D climate model experiments, obtained from the model II run of paper 1 which had specified climatological seasonally-varying ocean surface temperature and ocean ice cover. (a) is the geographical distribution of the annual-mean flux. (b) is the latitude/season distribution of the zonal-mean flux.

has been made by Miller et al. (1983), who show that the implied annual northward heat flux at the equator is 6.2×10^{14} W. With the ocean heat transport specified in this manner, the control run with computed ocean temperature has a simulated climate nearly the same as the documented model II. It is not identical, as a result of changes in the sea ice coverage which arise when the sea ice is a computed quantity. There is 15 percent less sea ice in the standard control run with computed ocean temperature than in the documented model II, as discussed below. This has local effects, mainly around Antarctica, but otherwise simulated quantities are practically identical to the documented model II climatology.

In our experiments with changed solar irradiance and atmospheric CO_2 we keep the ocean heat transport identical to that in the control run. Thus no ocean transport feedback is permitted in these experiments. Our rationale for this approach as a first step is its simplicity for analysis, and the fact that it permits a realistic atmospheric simulation.

Ocean ice cover is also computed in the experiments described here on the basis of the local heat balance. When the ocean surface loses heat, the mixed layer temperature decreases as far as the freezing point of ocean water, -1.6°C. Further heat loss from the open ocean causes ice to grow horizontally with thickness 1m until the gridbox is covered up to the limit set by the prescription for leads (open water). Still further heat loss causes the ice to thicken. Leads are crudely represented by requiring the fraction of open water in a gridbox to be greater than or equal to $0.1/z_{ice}$, where z_{ice} is the ice thickness in meters (paper 1).

Heat exchange between ocean ice and the mixed layer occurs by conduction in the climate model. A two-slab model is used for ice, with the temperature profile parabolic in each slab. This conduction is inefficient, and, if it were the only mechanism for heat exchange between the mixed layer and the ice, it would at times result in ocean ice coexisting with ocean water far above the freezing point; since this does not occur in nature, other mechanisms (such as lateral heat exchange) must contribute to the heat exchange. Therefore in our standard control run and S_0 and CO_2 experiments we impose the condition that the mixed layer temperature, which represents a mean for an 8° × 10° gridbox, not be allowed to exceed 0°C until all the ice in the gridbox is melted; i.e., if the mixed layer temperature reaches 0°C additional heat input is used to melt ice, decreasing its horizontal extent within the gridbox.

The annual mean sea ice cover in out standard control run is shown in Fig. 2b. Evidently there is too little sea ice in the model (15 percent less than the observations of Fig. 2a), especially at longitudes ~100°W and ~50°E in the Southern Hemisphere. Thus we also produced an alternate control run by removing the condition that all heat added to the mixed layer be used to melt ice if the mixed layer temperature reaches 0°C. This alternate control run has about 23 percent greater ocean ice cover (Fig. 2c) than observed, and thus the standard and alternate control runs bracket observations. We use the alternate control run for a second doubled CO_2 experiment, as one means of assessing the role of ocean ice in climate sensitivity.

In the following we first describe our standard S_0 and CO_2 experiments.

S_0 and CO_2 Experiments

S_0 was increased 2 percent and CO_2 was doubled (from 315 ppm to 630 ppm) instantaneously

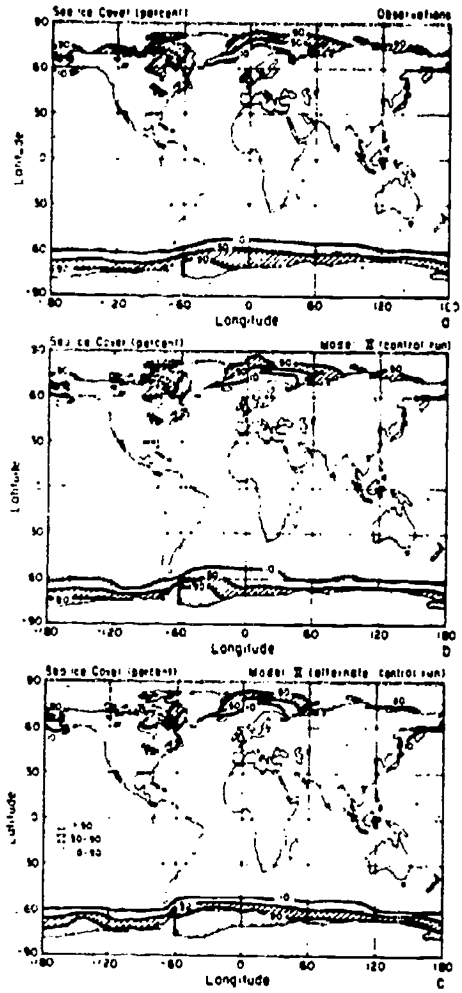

Fig. 2. Annual-mean sea ice cover. (a) observational climatology of Walsh and Johnson (1979) for the northern hemisphere and Alexander and Mobley (1976) for the southern hemisphere. (b) our standard control run of the 3-D climate model. (c) alternate control run, as described in the text.

on January 1 of year 1. Both experiments were run for 35 years. In this section we study the equilibrium response of the climate model to the S_0 and CO_2 forcings. The time dependence of the surface air temperature and the heat flux into the planetary surface are briefly noted, but only to verify that equilibrium has been achieved. The time dependence of these experiments is discussed in greater detail in a subsequent section concerned with the transient response of the climate system.

Global Mean Heat Balance and Temperature

Model II (paper 1) has a global annual mean net heat flux into the top of the atmosphere of 7.5 W m^{-2} (~2 percent of the insolation). 2.5 W m^{-2} of this imbalance is due to conversion of potential energy to kinetic energy (which is not reconverted to heat in the model) and computer truncation. The other global 5 W m^{-2} is absorbed by the ocean and ocean ice, at a rate of 7.1 W m^{-2} for the ocean surface area. This portion of the imbalance must be due to inaccuracies such as in the cloud properties, surface albedo, thermal emission calculations, etc. In our control run and experiments with computed ocean temperature we multiply the solar radiation absorbed at the ocean surface by the factor 0.96, which cancels the entire energy imbalance. The radiation correction factor has no appreciable direct effect on model sensitivity since all results are differenced against a control run; however, it does enable physical processes, such as condensation and ice melting, to operate at temperatures as realistic as possible. Together with the specified ocean transports, this allows the control run with computed ocean temperature to have essentially the same ocean temperature and climate as the model II run with fixed climatological ocean temperatures (paper 1).

The global mean heat flux into the planetary surface and surface air temperature are shown in Fig. 3 for the S_0 and CO_2 experiments. The heat flux peaks at ~3 W m^{-2} for both experiments; the radiative imbalance at the top of the atmosphere is essentially the same as this flux into the planetary surface, since the heat capacity of the atmosphere is small. Similar fluxes are expected in the two experiments because of the similar magnitudes of the radiative forcings. The 2 percent S_0 change corresponds to a forcing of 4.8 W m^{-2}. The initial radiative imbalance at the top of the atmosphere due to doubling CO_2 is only ~2.5 W m^{-2}, but after CO_2 cools the stratosphere (within a few months) the global mean radiative forcing is about 4 W m^{-2} (Fig. 4, Hansen et al., 1981). Over the ocean fraction of the globe we find a peak flux into the surface of 4-5 W m^{-2} in both experiments, of order 10 percent greater than the global mean forcing for an all-ocean planet. Thus heating of the air over land with subsequent mixing by the atmosphere increases the

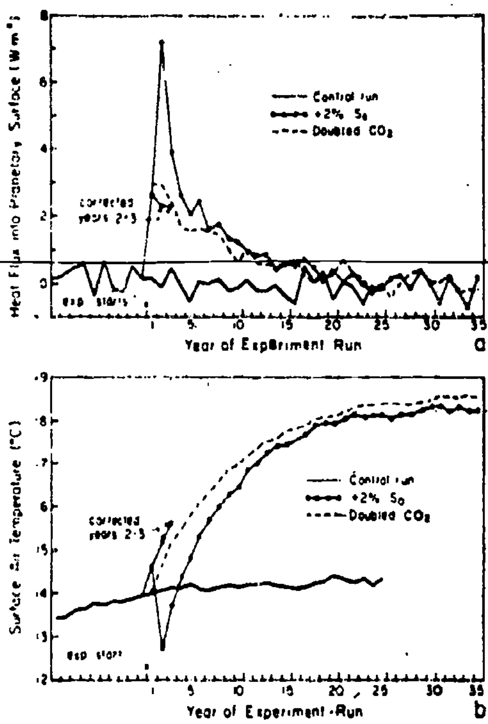

Fig. 3. Global net heat flux into planetary surface (a) and global surface air temperature (b). On April 1 of year 2 in the S_0 experiment the computer was hit by a cosmic ray or some other disturbance which caused improper numbers to be stored in the ground temperature array. This affected the temporal development of that run, but should not influence its equilibrium results. In order to determine the maximum heat flux into the ocean, the S_0 experiment was rerun for years 2 and 3 from March 31 year 2 thus eliminating the computer error for that period.

net heat flux into the ocean, but not by the ratio of global area to ocean area as assumed by Hansen et al. (1981). Apparently heating over continental areas is balanced substantially by increased cooling to space. A chief implication is that the time constant for the ocean to respond to global heating is longer than obtained from the common practice of averaging the ocean heat capacity over the entire globe (rather than over the ocean area).

The equilibrium global mean warming of the surface air is about 4°C in both the S_0 and CO_2 experiments. This corresponds to a feedback factor f = 3-4, since the no-feedback temperature change required to restore radiative equilibrium with space is ΔT_0 = 1.2-1.3°C. The heat flux and temperature approach their new equilibria with an e-folding time of almost a decade. We show in the section on transient climate response that the e-folding time is proportional to f, and that the value inferred from Fig. 3 is consistent with f = 3-4.

The mechanisms causing the global warmings in these experiments are investigated below, including presentation of the global distribution of key changes. These results are the means for years 26-35 of the control and experiment runs. Fig. 3 indicates that this should provide essentially the equilibrium response, since by that time the heat flux into the ocean is near zero and the temperature trend has flattened out.

Global Temperature Changes

The temperature changes in the S_0 and CO_2 experiments are shown in Fig. 4 for the annual mean surface air temperature as a function of latitude and longitude, the zonal mean surface air temperature as a function of latitude and month, and the annual and zonal mean temperature as a function of altitude and latitude. We discuss the nature and causes of the temperature changes, and then make a more quantitative analysis below using 1-D calculations and the alternate CO_2 experiment with changed sea ice prescription.

The surface air warming is enhanced at high latitudes (Fig. 4, upper panel) partly due to the greater atmospheric stability there which tends to confine the warming to the lower troposphere, as shown by the radiation changes discussed below and the experiment with altered sea ice.

There is a very strong seasonal variation of the surface warming at high latitudes (Fig. 4, middle panel), due to the seasonal change of atmospheric stability and the influence of melting sea ice in the summer which limits the ocean temperature rise. At low latitudes the temperature increase is greatest in the upper troposphere (Fig. 4, lower panel), because the added heating at the surface primarily causes increased evaporation and moist convection, with deposition of latent heat and water vapor at high levels.

The statistical significance of these results can be verified from Fig. 5, which shows the standard deviation for the last 10 years of the control run for all the quantities in Fig. 4, and

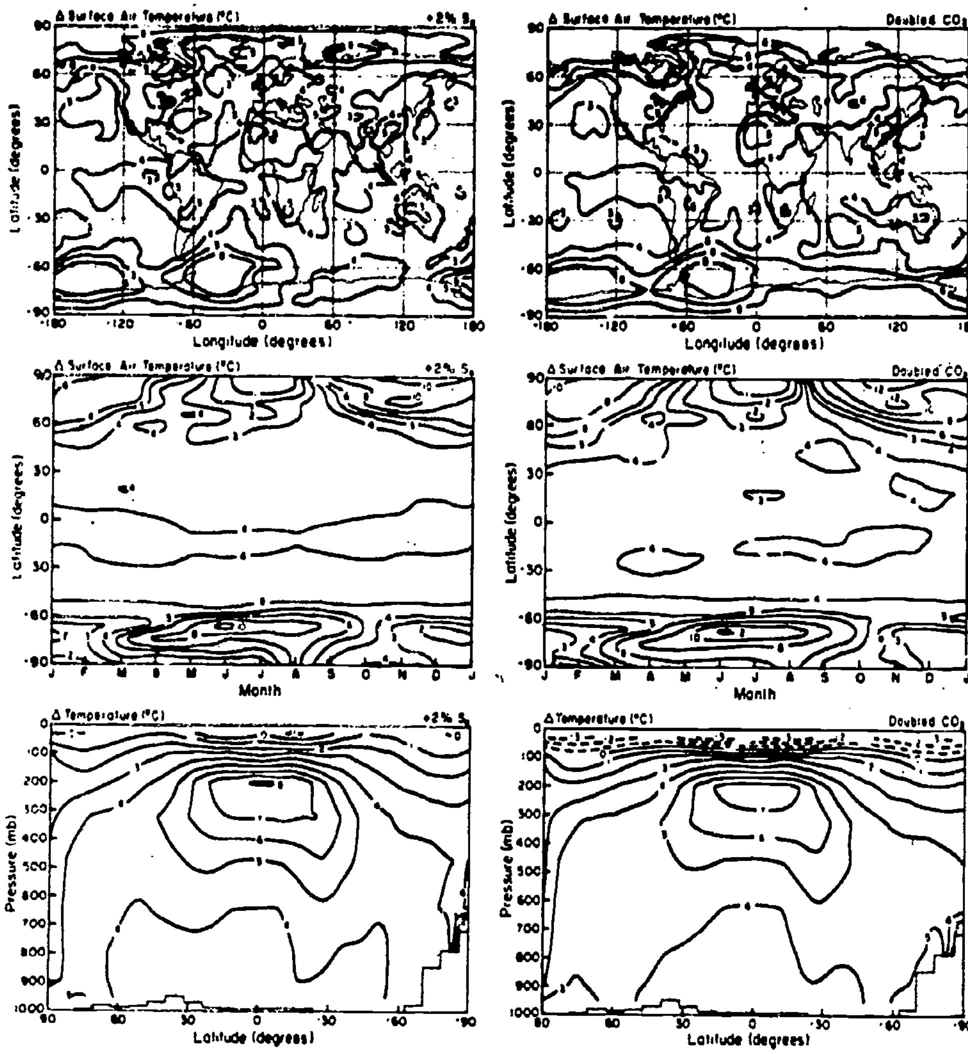

Fig. 4. Air temperature change in the climate model for a two percent increase of solar irradiance (left) and for doubled atmospheric CO_2 (right). The upper graphs show the geographical distribution of annual mean surface air warming, the middle graphs show the seasonal variation of the surface air warming averaged over longitude, and the lower graphs show the altitude distribution of the temperature change averaged over season and longitude.

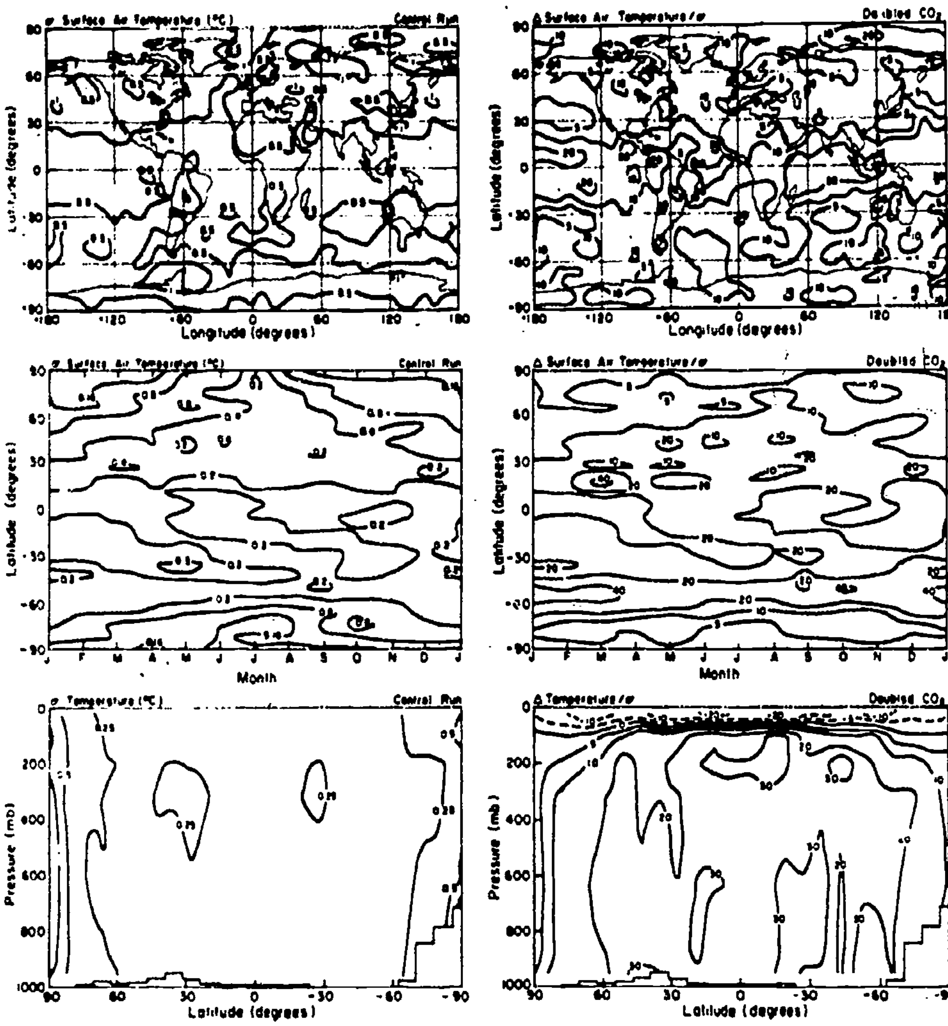

Fig. 5. Left side: standard deviation of temperature for the last 10 years in the control run. Right side: ratio of temperature change for years 26-35 of the doubled CO_2 experiment to the standard deviation of temperature in the control run.

the ratio of the change of the quantity in the doubled CO_2 experiment to the standard deviation. The standard deviation is computed routinely for all of the quantities output from our 3-D model. We only discuss changes in the experiment runs which are far above the level of model fluctuations or 'noise' in the control run.

The patterns of temperature change are remarkably similar in the S_0 and CO_2 experiments, suggesting that the climate response is to first order a function of the magnitude of the radiative forcing. The only major difference is in the temperature change as a function of altitude; increased CO_2 causes substantial stratospheric cooling. This similarity suggests that, to first order, the climate effect due to several forcings including various tropospheric trace gases may be a simple function of the total forcing.

The global mean warming of surface air that we obtain for doubled CO_2 is similar to that obtained by Manabe and Stouffer (1980) for quadrupled CO_2. This large difference in sensitivity of the two models appears to be associated mainly with the feedback mechanisms in the models, as discussed below. The patterns of the temperature changes in the two models show gross similarities, but also significant differences. We defer detailed comparison of the model results until after discussion of the feedback mechanisms.

1-D Analysis of Feedbacks in 3-D Experiments

The processes chiefly responsible for the temperature rise in the 3-D model can be investigated with a 1-D radiative convective (RC) climate model. We use the 1-D model of Lacis et al. (1981) to evaluate the effect of changes in radiative forcing that take place in the 3-D model experiments. As part of the 3-D model diagnostics, we have available global average changes in surface and planetary albedo, and changes in amount and vertical distribution of clouds, water vapor and atmospheric lapse rate. We insert these changes one-by-one, or in combination, into the 1-D model and compute the change in global surface temperature. We employ the usual 'convective adjustment' procedure in our 1-D calculations, but with the global mean temperature profile of the 3-D model as the critical lapse rate in the troposphere. Contrary to usual practice, we allow no feedbacks to operate in the 1-D calculations, making it possible to associate surface temperature changes with individual feedback processes.

There is no a priori guarantee that the net effect of these changes will yield the same warming in the 1-D model as in the 3-D model, because simple global and annual averages of the changes do not account for the nonlinear nature of the physical processes and their 2-D and 3-D interactions. Also, changes in horizontal dynamical transports of heat and moisture are not entered explicitly into the 1-D model; the effects of dynamical feedbacks are included in the radiative factors which they influence, such as the cloud cover and moisture profile, but the dynamical contributions are not identified. Nevertheless, this exercise provides substantial information on climate feedbacks. Determination of how well the 1-D and 3-D results correspond also is a useful test for establishing the value of 1-D global climate models.

The procedure we use to quantify the feedbacks is as follows. The increase of total water vapor in the 3-D model (33 percent in the S_0 experiment) is put in the 1-D model by multiplying the water vapor amount at all levels by the same factor (1.33); the resulting change in the equilibrium surface temperature of the 1-D model defines the second bars in Fig. 6. Next the water vapor at each level in the 1-D model is increased by the amount found in the 3-D experiment; the temperature change obtained in the first (total H_2O amount) test is subtracted from the temperature change obtained in this test to obtain the temperature change credited to the change in water vapor vertical distribution. The change of temperature gradient (lapse rate) between each pair of levels in the 3-D model is inserted in the control 1-D model to estimate the effect of lapse rate change on surface temperature, shown by the fourth bars in Fig. 6. Since the lapse rate changes are due mainly to changes of water vapor, we take the net of these three temperature changes in the 1-D model as our estimate of the water vapor contribution to the total temperature change. The global mean ground albedo change in the 3-D model (defined as the ratio of the global mean upward and downward solar radiation fluxes at the ground) is inserted into the 1-D control run to obtain our estimate of the ice/snow albedo contribution to the temperature change.

Cloud contributions are more difficult to analyze accurately because of the variety of cloud changes that occur in the 3-D model (see below), including changes in cloud overlap, and the fact that the changes do not combine linearly. We first estimate the total cloud impact by changing the cloud amounts at all levels in the 1-D model in proportion to changes obtained in the 3-D model. The total cloud effect on the temperature obtained in this way is subdivided by defining a portion to be due to the cloud cover change (by running the 1-D model with a uniform change of all clouds so as to match the total cloud cover change in the 3-D model) and by assigning the remainder of the total cloud effect to cloud height changes. These assumptions involve some arbitrariness. Nevertheless, the resulting total temperature changes in the 1-D model are found to be within 0.2°C of the global mean temperature changes in the 3-D experiments, providing circumstantial evidence that the procedure takes into account the essential radiative aspects of cloud

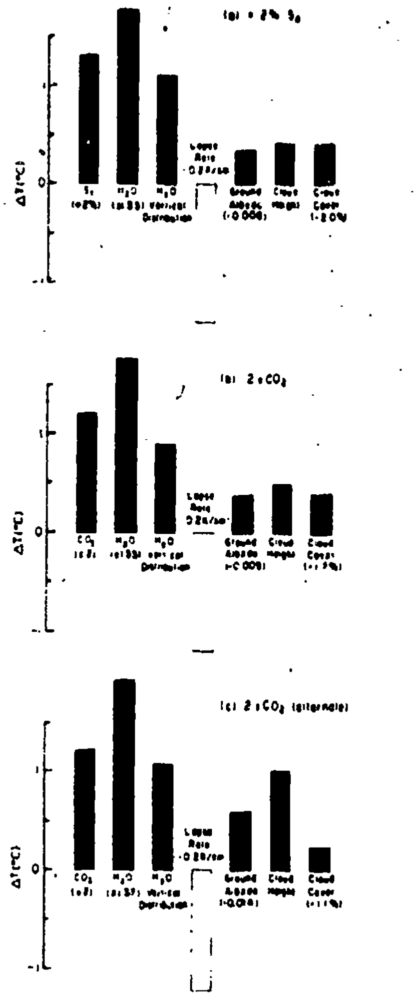

Fig. 6. Contributions to the global mean temperature rise in the S_0 and CO_2 experiments as estimated by inserting changes obtained in the 3-D experiments into 1-D radiative convective model. (a) +2 percent S_0 experiment, (b) doubled CO_2 experiment, and (c) doubled CO_2 experiment for alternate control run with greater sea ice.

cover change.

The temperature changes in the 1-D model are shown in Fig. 6 for the standard S_0 and CO_2 experiments, and the CO_2 experiment with alternate sea ice computation. Resulting gains and feedback factors are given in Table 1.

Water vapor feedback. Water vapor provides the largest feedback, with most of it caused by the increase of water vapor amount. Additional positive feedback results from the water vapor distribution becoming weighted more to higher altitudes, but for the global and hemispheric means this is approximately cancelled by the negative feedback produced by the changes in lapse rate, also due mainly to the added H_2O. The near cancellation of these two effects is not surprising, since the amount of water the atmosphere holds is largely dependent on the mean temperature, and the temperature at which the infrared opacity occurs determines the infrared radiation. This tendency for cancellation suggests that the difficulty in modeling moist convection and the vertical distribution of water vapor may not have a great impact on estimates of global climate sensitivity (excluding the indirect effect on cloud distributions).

The net water vapor gain thus deduced from the 3-D model is $g_W \sim 0.4$, or a feedback factor $f_W \sim 1.6$. The same sensitivity for water vapor is obtained in 1-D models by using fixed relative humidity and fixed critical lapse rate (Manabe and Wetherald, 1967), thus providing some support for that set of assumptions in simple climate models. Relative humidity changed only slightly in our 3-D experiments; for example, in our standard doubled CO_2 experiment the average relative humidity increased 0.015 (1 = 100 percent humidity), with a 0.06 global increase at 200 mb being the largest change at any altitude. This compares with an increase of mean specific humidity of 33 percent. The global mean lapse rate change in the 3-D model (-0.2°C km^{-1}) is less than the change of the moist adiabatic lapse rate (-0.3°C km^{-1}), the decrease at low latitudes being partly offset by an increase at high latitudes. And, as explained above, the effect of the lapse rate change on temperature is largely balanced by the effect of the resulting displacement of water vapor to greater altitude.

Snow/ice feedback. Ground albedo decrease also provides a positive feedback. The ground albedo change (upper panel of Fig. 7) is largely due to reduced sea ice. Shielding of the ground by clouds and the atmosphere (middle panel of Fig. 7) makes this feedback several times smaller than it would be in the absence of the atmosphere. However, it is a significant positive feedback and is at least as large in the Southern Hemisphere as in the Northern Hemisphere. The geographic pattern of the temperature increase (Fig. 4) and the coincidence of warming maxima with reduced sea ice confirm that the sea ice effect is a substantial positive feedback.

Further insight into the sea ice feedback is

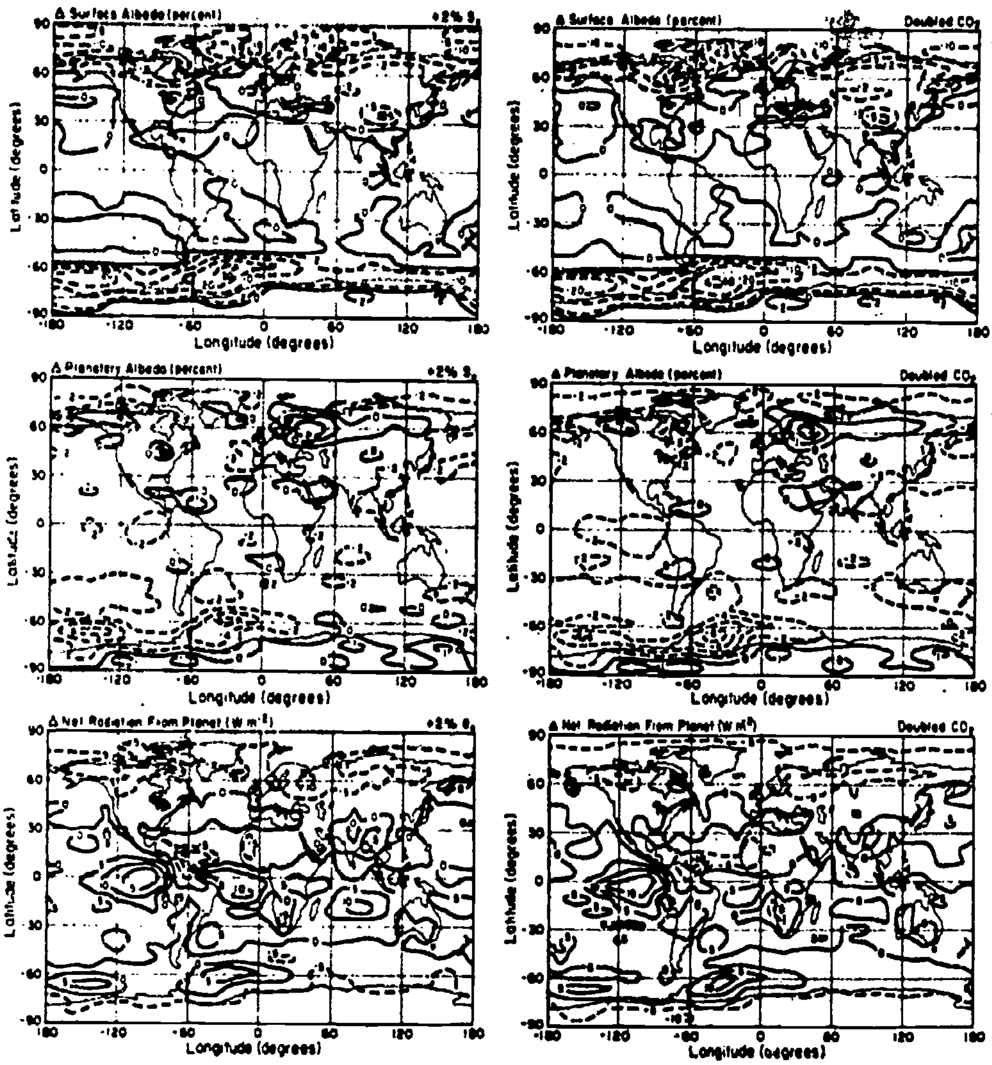

Fig. 7. Annual mean radiation changes in the climate model for two percent increase of S_0 (left) and doubled CO_2 (right). In Figs. 7, 8, 10 and 11 "percent" change refers to the full range of the quantity, e.g., a change from 60 percent albedo to 50 percent albedo is defined to be a 10 percent change.

provided by the experiment with alternate prescription for computing sea ice cover. The greater sea ice cover in the control run for this experiment permits a greater surface albedo feedback, as indicated by the analysis with the 1-D model shown in Fig. 6c. These results illustrate the sensitivity of a system which already contains large positive feedbacks, the gain due to increased surface albedo being augmented by increased water vapor and cloud gains.

Based on these experiments, we estimate the sea ice/snow feedback factor as ~1.1. However, this value refers to a climate change from today's climate to a climate which is warmer by about 4°C. We expect $f_{snow/ice}$ to decrease as the area of sea ice and snow decreases, so its value is probably somewhat larger in the limit of a small increment about today's climate. Also, the prescription for computing sea ice in our standard experiments (which gives 15 percent too little sea ice for today's climate) probably causes an underestimate of $f_{snow/ice}$, as indicated by the value inferred for f in the experiment with altered sea ice prescription (which yielded 23 percent too much sea ice for today's climate).

The gain we obtain for ice/snow feedback in our 3-D model (~0.1) agrees well with the value (0.12) obtained by Wang and Stone (1980) from a 1-D radiative convective model. The feedback is much smaller than early estimates such as those of Budyko (1969) and Sellers (1969), who assigned a large albedo increment to ice/snow, but did not account for cloud shielding, vegetation masking of snow, and zenith angle variation of albedo (North, 1975; Lian and Cess, 1977).

Cloud feedback. Cloud changes (Fig. 9) also provide a significant positive feedback in this model, as a result of a small increase in mean cloud height and a small decrease in cloud cover. The gain we obtain for clouds is 0.22 in our standard doubled CO_2 experiment. This happens to be similar to the gain of 0.19 which is obtained in 1-D models if the cloud cover is kept fixed and the cloud height is determined by the assumption of fixed cloud temperature (Cess, 1974). However, a substantial part of the cloud gain in the 3-D model is due to the cloud cover change (Fig. 6). The portion of the cloud gain associated with cloud height change in the S_0 experiment and the standard doubled CO_2 experiment is about midway between the two common assumptions used in simple climate models: fixed clouds altitude (gain = 0) and fixed cloud temperature (gain 0.2).

The cloud height and cloud cover changes in the 3-D model seem qualitatively plausible. The reduced cloud cover primarily represents reduction of low and middle level clouds, due to increased vertical transport of moisture by convection and the large scale dynamics. The increase of high level cirrus clouds at low latitudes is consistent with the increase of penetrating moist convection at those latitudes. However, the cloud prescription scheme in the model (paper 1) is highly simplified; for example, it does not incorporate a liquid water budget for the cloud droplets or predict changes in cloud optical thickness at a given height. Thus the possibility of an increase in mean cloud optical thickness with the increased water vapor content of the atmosphere is excluded. Indeed, because the cloud optical thickness decreases with increasing altitude (paper 1), the increase of cloud height causes a decrease of optical thickness. This is a positive feedback for low and middle level clouds, but a negative feedback for cirrus clouds, which are a greenhouse material with suboptimal optical thickness. As a crude test of possible effects of changes in cloud optical thickness we let the cloud optical thickness in the 1-D model change in proportion to the absolute humidity; this practically eliminated the positive cloud feedback, i.e., it resulted in f_{clouds} ~ 1.0. Clearly, assessment of the cloud contribution to climate sensitivity depends crucially upon development of more realistic representation of cloud formation processes in climate models, as verified by an accurate global cloud climatology.

Summary of model feedbacks. Given the cancellation between the change in lapse rate and change in vertical distribution of water vapor, the processes providing the major radiative feedbacks in this climate model are total atmospheric water vapor, clouds and the surface albedo. Considering the earth from a planetary perspective, it seems likely that these are the principal feedbacks for the earth on a time scale of decades. The albedo of the planet for solar radiation is primarily determined by the clouds and surface, with the main variable component of the latter being the ice/snow cover. The thermal emission of the planet is primarily determined by the atmospheric water vapor and clouds. Thus the processes principally responsible for the earth's radiation balance and temperature are included in the 1-D model, and we have shown that these processes are the source of the primary radiative feedbacks in our 3-D model.

Table 1 summarizes the gains and feedback factors inferred from the changes which occurred in our 3-D model experiments, and the corresponding temperature changes for different combinations of these feedback processes. Note again that effects of dynamical feedbacks are implicitly included in these changes. The temperature changes illustrate the nonlinear way in which feedback processes combine (Eq. (3)). For example, the ice/snow feedback adds about 1°C to the temperature response, but if the water vapor and cloud feedbacks did not exist the ice/snow feedback would add only a few tenths of a degree to the sensitivity. This nonlinear behavior is a result of the fact that when the ice/snow feedback occurs in the presence of the other (positive) feedbacks, it enhances the water vapor and cloud changes.

Comparison to Manabe and Stouffer. This analysis of the feedbacks in our model provides an

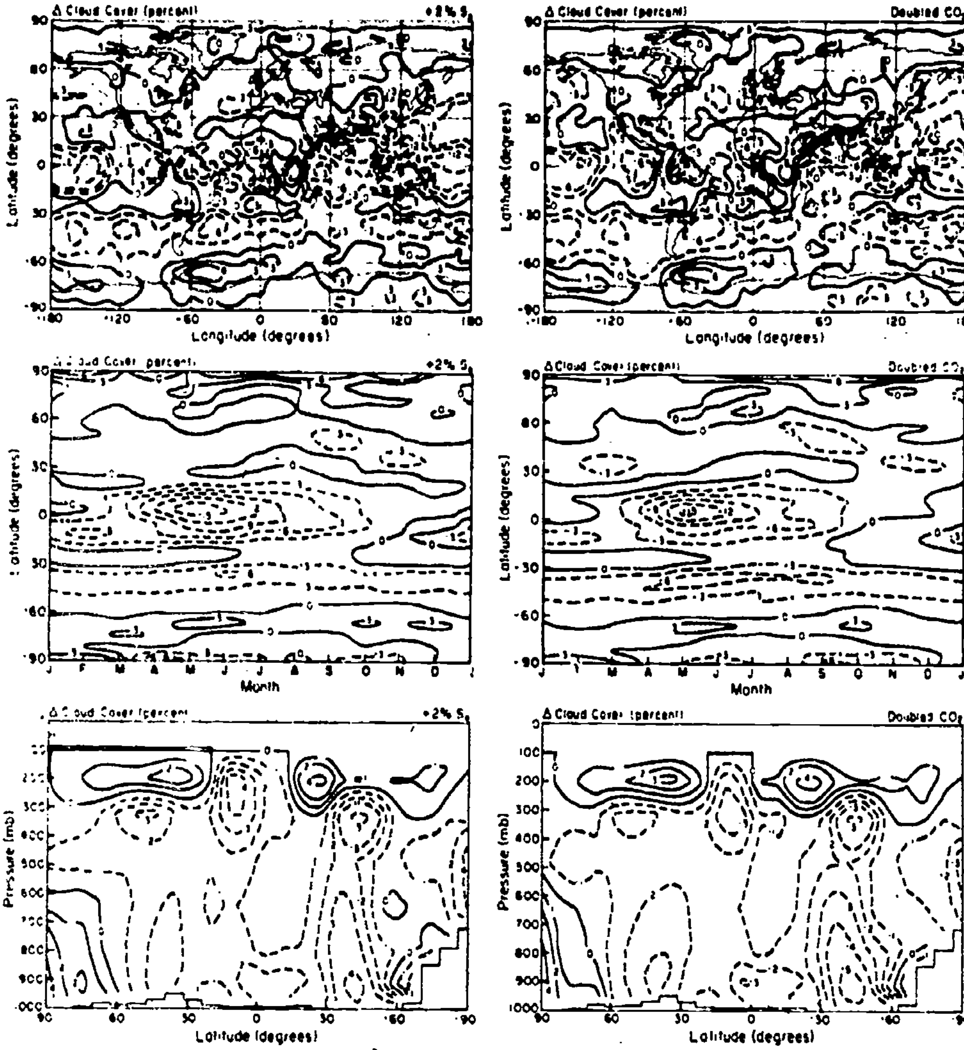

Fig. 8. Cloud changes in the climate model for two percent increase of S_0 (left) and doubled CO_2 (right). The upper graphs show the geographical distribution of annual mean cloud cover change, the middle graphs show the seasonal variation of cloud cover change averaged over longitude, and the lower graphs show the altitude distribution of the cloud cover change averaged over season and longitude.

TABLE 1. Gain (g), feedback factor (f) and equilibrium temperature changes (ΔT) inferred from calculations with 1-D radiative-convective model for global mean changes in the 3-D GCM experiments. The subscripts w, c and s refer to water vapor, clouds and surface albedo. g is obtained as the ratio of the temperature change in the 1-D model (with only the indicated processes included) to the global mean temperature change in the 3-D experiment. f is from $f_i = 1/(1 - g_i)$. ΔT is the equilibrium surface air warming computed with the 1-D model for global mean changes of 3-D model constituents with only the indicated processes included; ΔT_0 includes only the indicated radiative forcing, without feedbacks.

	Experiment		
	+2% S_0	Doubled CO_2	Alternate Doubled CO_2
g_w	0.37	0.40	0.37
g_c	0.20	0.22	0.28
g_s	0.09	0.09	0.12
f_w	1.59	1.66	1.58
f_c	1.26	1.29	1.34
f_s	1.09	1.10	1.14
f_{wc}	2.38	2.62	2.67
f_{wcs}	2.96	3.45	3.95
ΔT_0	1.3	1.2	1.2
ΔT_{0w}	2.1	2.0	1.9
ΔT_{0c}	1.7	1.6	1.6
ΔT_{0s}	1.5	1.3	1.4
ΔT_{0wc}	3.2	3.2	3.2
ΔT_{0wcs}	4.0	4.2	4.8

indication of the causes of the difference between our climate model sensitivity and that of Manabe and Stouffer (1980). They infer a warming of 2°C for doubled CO_2, based on an experiment with quadrupled CO_2 which yielded 4°C warming. Their model had fixed clouds (altitude and cloud cover), thus $f_{cloud} \equiv 1$. Also their control run had less sea ice than our model, so their $f_{sea\ ice}$ should be between 1 and the value (~1.1) for our model. It is apparent from Table 1 that differences arising from the treatments of these two processes may account for most of the difference in global climate sensitivity.

Another major difference between our model and the model of Manabe and Stouffer is that we include a specified horizontal transport of heat by the ocean. This transport is identical in our control and experiment runs, i.e., the changed climate is not allowed to feed back on the ocean circulation. Of course Manabe and Stouffer do not allow feedback on ocean transport either, since the ocean transport is zero in both experiment and control. However, some other mechanisms must replace oceanic poleward transport of heat in their model, since their high latitude temperatures are at least as warm as in our model (and observations). Enhanced poleward transport of latent and sensible heat by the atmosphere must be the mechanism replacing ocean heat transport in their model. This atmospheric transport is expected to provide a negative feedback (Stone, 1984), and indeed the total atmospheric energy transport did decrease poleward of 50°C latitude in the CO_2 experiments of Manabe and Wetherald (1975, 1980). It is not obvious whether the ocean transport feedback is positive or negative in the real world.

The contribution of ocean heat transport to climate sensitivity, like that of the atmospheric transports, does not appear as an identified component in an energy balance analysis such as in Fig. 8. This is irrelevant for our model, since it has no ocean transport feedback. However, in models which calculate the ocean heat transport or a surrogate energy transport, this feedback is included implicitly as a (positive or negative) portion of identified components of ΔT ($\Delta T_{water\ vapor}$, ΔT_{clouds}, $\Delta T_{ice/snow}$). The portion of these changes due to this feedback process could be identified by running those models with fixed (climatological) ocean heat transport.

Manabe (1983) suggests that our ice/snow feedback is unrealistically large and accounts for most of the difference between our climate model sensitivity and that of Manabe and Stouffer (1980). However, as summarized in Table 2, the amount of sea ice in the control run for our standard CO_2 experiment is actually somewhat less than observed sea ice cover. In our alternate CO_2 experiment, with sea ice cover greater than in observations, the ice/snow feedback increases significantly, suggesting that the ice/snow feedback in our standard experiment may be an underestimate. Also, we show in the next section that the sea ice feedback for the climate change from 18K to today, a warming of about 4°C, is about twice as large as in our doubled CO_2 experiments; this 18K sea ice feedback factor is based on measured changes of sea ice cover. The small ice/snow feedback in Manabe and Stouffer's model may be a result of their model being too warm at high latitudes; indeed, in the Southern Hemisphere (where the sea ice feedback is greatest in our model and in 18K measurements) their control run has almost no ice in the summer. Another likely reason for Manabe and Stouffer's albedo feedback being weaker is the stronger negative feedback in their meridional dynamical flux, as a result of that flux all being carried in the atmosphere. We conclude that our estimate for the sea ice feedback is conservative, i.e., it is more likely to be in error on the low side than on the high side.

We obtain a greater warming at low latitudes (~3-4°C for doubled CO_2) than that found by Manabe and Stouffer (~3°C for quadrupled CO_2),

TABLE 2. Annual-mean sea ice cover as fraction of global or hemispheric area in several 3-D experiments. In run 1 the sea ice cover is specified to be today's climatology of Alexander and Mobley (1976) for the Southern Hemisphere and Walsh and Johnson (1979) for the Northern Hemisphere. Run 7 specifies the sea ice cover according to CLIMAP data for 18K (CLIMAP, 1981) and run 11 modifies the Southern Hemisphere CLIMAP data as discussed in the section on ice age experiments. In other runs the sea ice cover is computed.

		Sea Ice Cover		
Run	Experiment Description	Globe	Northern Hemisphere	Southern Hemisphere
1	Model II, Run 61 of paper 1; sea ice specified as today's climatology	0.048	0.042	0.054
2	Control run for standard CO_2 and S_0 experiments	0.041	0.039	0.043
3	Standard 2 × CO_2 experiment	0.023	0.028	0.017
4	Standard +2% S_0 experiment	0.025	0.030	0.020
5	Control run for alternate CO_2 experiment	0.060	0.046	0.073
6	Alternate 2 × CO_2 experiment	0.031	0.033	0.029
7	CLIMAP boundary conditions	0.089	0.048	0.131
11	CLIMAP boundary conditions with modified Southern Hemisphere sea ice	0.077	0.048	0.106

We analyzed the contributions to the warming in our 3-D model as a function of latitude by inserting all zonal-mean radiative changes into the 1-D radiative-convective model. At low latitudes (0-30°) the clouds contribute a positive feedback of about 1-1.5°C; the larger part of this, nearly 1°C, is due to reduction of low level cloud cover with doubled CO_2, with increase of cirrus clouds contributing a smaller positive feedback. At high latitudes (60-90°) the clouds contribute a smaller negative feedback (0-1°C), due to increased low level clouds; this cloud increase (Fig. 8) probably is due to increased evaporation resulting from the reduced sea ice cover. The computed distributions of water vapor may also contribute to the difference between our result and that of Manabe and Stouffer. For example, in our model low latitude relative humidity at 200 mb increased by 0.085 with doubled CO_2. The cloud and water vapor characteristics depend on the modeling of moist convection and cloud formation; Manabe and Stouffer use the moist adiabatic adjustment of Manabe et al. (1965) and fixed clouds; we use a moist convection formulation which allows more penetrative convection (paper 1) and cloud formation dependent on local saturation. Presently available cloud climatology data has not permitted detailed evaluation of these moist convection and cloud formation schemes.

The high latitude enhancement of the warming is less in our model than in observed temperature trends for the past 100 years (Hansen et al., 1983a). If this observed high latitude enhancement also occurs for large global temperature increases, the smaller high latitude enhancement in our 3-D model suggests the possibility that the 3-D model has either overestimated the low latitude climate sensitivity (probably implicating the low latitude cloud feedback) or underestimated the high latitude sensitivity. If the former case is correct, the global climate sensitivity implied by the 3-D model may be only 2.5-3°C; but if the latter interpretation is correct, the global climate sensitivity may be greater than 4°C. A more precise statement requires the ability to analyze and verify the cloud feedback on a regional basis.

Conclusion. Atmospheric water vapor content provides a large positive feedback, and we find that in our model the effects of changes in lapse rate and water vapor vertical distribution largely cancel (for global or hemispheric means). The existence of the strong positive water vapor feedback implies that moderate additional positive feedback can greatly increase climate sensitivity.

because of the nonlinear way in which feedbacks combine. In our model, sufficient ice/snow feedback occurs to increase the global sensitivity to ~2.5°C, and with cloud feedback to ~4°C for doubled CO_2. Although the cloud feedback is very uncertain, our 3-D study suggests that it is in the range from approximately neutral to strongly positive in global mean, and thus that global climate sensitivity is at least 2.5°C for doubled CO_2. The magnitudes of the global ice/snow and cloud feedbacks in our 3-D model are plausible, but confirmation requires improved ability to accurately model the physical processes as well as empirical tests of the climate model on a variety of time scales.

Ice Age Experiments

Records of past climate provide a valuable means to test our understanding of climate feedback mechanisms, even in the absence of a complete understanding of what caused the climate change. In this section we use the comprehensive reconstruction of the last ice age (18,000 years ago) compiled by the CLIMAP project (CLIMAP project members, McIntyre, project leader, 1981; Denton and Hughes, 1981). We first run our climate model with the 18K boundary conditions as specified by CLIMAP; this allows us to estimate the global mean temperature change between 18K and today. We then rerun the model changing feedback processes one-by-one and note their effect on the planetary radiation balance at the top of the atmosphere. This provides a measure of the gain or feedback factor for each process. We also examine the model for radiation balance when all of the known 18K feedbacks are included; this allows some inferences about the model sensitivity and the accuracy of the CLIMAP data. Finally, we compare different contributions to the 18K cooling; by considering the land ice and atmospheric CO_2 changes as slow or specified global climate forcings, we can infer empirically the net feedback factor for processes operative on 10-100 year time scales.

Global maps of the CLIMAP 18K boundary conditions, including the distributions of continental ice, sea ice and sea-surface temperature, are given by CLIMAP (1981) and Denton and Hughes (1981). These boundary conditions, obtained from evidence such as glacial scouring, ocean sediment cores containing detritus rafted by sea ice, and oxygen isotopic abundances in snowfall preserved in Greenland and Antarctic ice sheets, necessarily contain uncertainties. For example, Burckle et al. (1982) suggest that the CLIMAP Southern Hemisphere sea ice cover may be overestimated, and DiLabio and Klassen (1983) argue that the CLIMAP 'maximum extent' ice sheet model may be an overestimate. Questions have also been raised about the accuracy of the ocean surface temperatures, especially at low latitudes (Webster and Streten, 1978). We examine quantitatively the effect of each of these uncertainties on our feedback analyses.

Simulated 18K Climate Patterns

Our 18K simulation was obtained by running climate model II (paper 1) with the CLIMAP (1981) boundary conditions. The boundary conditions included the earth orbital parameters for that time (Berger, 1979). The run was extended for six years, with the results averaged over the last five years to define the 18K simulated climate. The control run was the five year run of model II with today's boundary conditions, which is documented in paper 1.

__Temperature.__ Simulated 18K temperature patterns are shown in Fig. 9. The temperatures in the model, especially of surface air, are constrained strongly by the fixed boundary conditions, and thus their accuracy is dependent mainly on the reliability of the CLIMAP data.

Global surface air temperature in the 18K experiment is 3.6°C cooler than in the control run for today's boundary conditions. Much greater cooling, exceeding 20°C, occurs in southern Canada and northern Europe and cooling of more than 5°C is calculated for most of the Southern Hemisphere sea ice region. Some high latitude regions, including Alaska and parts of Antarctica, are at about the same temperature in the 18K simulation as today; thus there is not universal high latitude enhancement of the climate change.

Temperature changes over the tropical and subtropical oceans are only of the order of 1°C, and include substantial areas that are warmer in the 18K simulation than today. The latter aspect requires verification; diverse areas of the tropics and subtropics experienced mountain glaciation at 18K with snowline descent of about 1km, and pollen data indicate substantial cooling of the order of 5°C at numerous low latitude areas. As indicated by our 3-D model experiment the CLIMAP sea surface temperatures are inconsistent with the observations of tropical cooling, since specification of relatively warm tropical and subtropical ocean temperatures effectively prohibits large cooling over land at these latitudes. We conclude that the low latitude ocean temperatures are probably overestimated in the CLIMAP data. A more quantitative analysis (Rind and Peteet, in preparation) suggests that large areas in the low latitude oceans may be too warm by 2-3°C in the CLIMAP data.

The middle parts of Fig. 9 show that the cooling at 18K occurred especially in the fall and winter. Although the surface air was substantially colder all year at latitude 60°N, this was largely a result of the change in mean surface altitude caused by the presence of ice sheets; the cooling at fixed altitude is considerably less. The zonal mean surface air in the tropics was cooler all year. The lower parts of Fig. 9 show substantial cooling throughout most of the troposphere. At high latitudes the greatest cooling occurs in the lower troposphere.

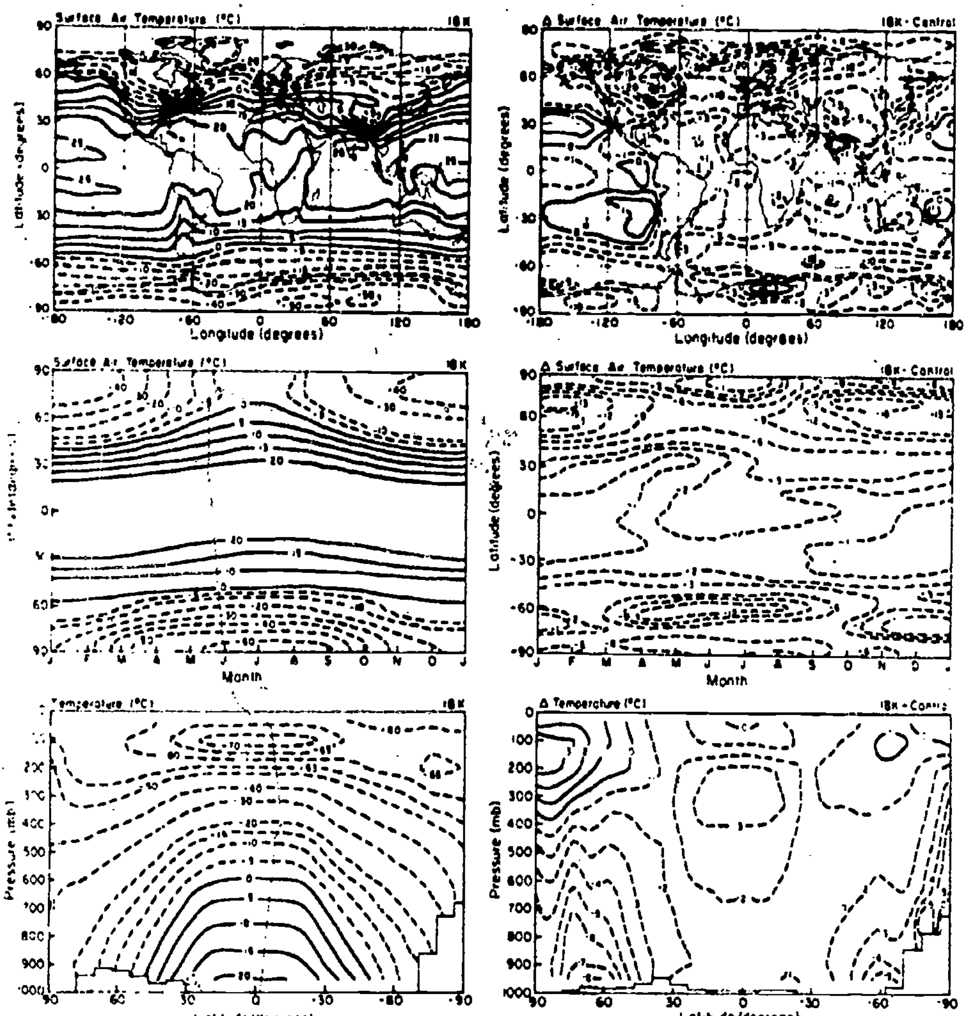

Fig. 9. Air temperature in the climate model experiment with boundary conditions for the ice age 18,000 years ago (left) and the temperature difference between the 18K simulation and the control run for today's climate boundary conditions (right). The control run is described in detail in paper 1.

Radiation. Changes in the planetary radiation budget in the 18K simulation are shown in Fig. 10. The surface albedo increases as much as 0.45 in the regions of ice sheets over northern Europe and southern Canada and about 0.30 in regions of large changes in sea ice coverage. Shielding by the atmosphere and the large zenith angles reduce the impact on planetary albedo to 0.15-0.20 over the ice sheets and 0.05-0.10 over sea ice. The effect of the planetary albedo change on the net radiation from the planet is partially compensated over the ice sheets by reduced thermal emission, but nearly the full effect of the albedo change appears in the net radiation change over sea ice; these conclusions follow from comparison of the middle and lower parts of Fig. 10 and the fact that an albedo change of 0.10 is equivalent to 24 W m^{-2}. Most of the more detailed changes in the geographical patterns of the radiation budget are associated with changes of cloud cover or cloud top altitude.

Clouds. Cloud changes in the 18K simulation are illustrated in Fig. 11. There is a significant reduction of cloud cover in regions with increased sea ice, probably because of the reduced evaporation in those regions. The zonal mean cloud cover decreases slightly in the tropics during most of the year, increases slightly in the subtropics and increases at Northern Hemisphere midlatitudes in summer. The polar regions exhibit opposite behavior; at the north pole (a region of sea ice) the clouds decrease, while at the south pole (a continental region of high topography) the clouds increase in the 18K experiment. The lowest panel in Fig. 11 shows that the high level (cirrus) clouds are reduced substantially in the 18K simulation, presumably due to the reduction of penetrating moist convection and its associated transport of moisture. Most of these changes are consistent with those in the doubled CO_2 experiment, the cloud changes at 18K being the opposite of those which occur for the warmer doubled CO_2 climate.

Summary. The global mean surface air cooling of the Wisconsin ice age (compared to today) is computed from the CLIMAP boundary conditions to be ~4°C. Thus the mean temperature change between 18K and today is very similar to the projected warming for doubled CO_2. Below we analyze the contributions of different feedback processes to this global climate change.

18K Feedback Factors

We perform two types of experiments to study the feedback processes at 18K. In experiments of the first type, a given factor is modified (say the sea ice cover is changed) and the model is run for several years with the atmosphere free to adjust to the change, but with the ocean temperature and other boundary conditions fixed. Thus the only substantial feedback factors allowed to operate are water vapor and clouds (snow over land and ice can also change, but this represents only a small part of the ice/snow feedback). Experiments of this type enable us to relate surface temperature changes with flux imbalances at the top of the atmosphere under conditions of radiative/dynamic equilibrium in the atmosphere. Results of this type of experiment are summarized in the first part of Table 3 (experiments 8-14) along with the 18K control run (experiment 7). The method for converting the flux imbalance at the top of the atmosphere in these experiments to gain or feedback factors is described below in conjunction with experiment 8.

Experiments of the second type (labeled with a star (*) and tabulated in the lower part of Table 3) provide a faster, but more approximate, method for evaluating feedbacks which can be applied to certain types of radiative forcing. In the starred experiments we determinn the radiative forcing by changing a factor in the control run (say sea ice cover) and calculating the instantaneous change in the planetary radiation balance at the top of the atmosphere. The atmospheric temperature and other radiative constituents and boundary conditions are not allowed to change; thus no feedbacks operate in these experiments. The flux change at the top of the atmosphere, ΔF, defines a change of planetary effective temperature

$$\Delta T_e(°C) = (\sigma T_e^3)^{-1}\Delta F(W\ m^{-2}) \sim 0.27\Delta F(W\ m^{-2}) \quad (13)$$

for T_e = 255K. This relation provides a good estimate of the no-feedback contribution to the equilibrium surface temperature change, if the radiative perturbation does not appreciably alter the vertical temperature structure. This procedure is applicable to solar flux, surface albedo and certain tropospheric gas perturbations (Hansen et al., 1982), but does not work as simply for CO_2 perturbations, because CO_2 cools the stratosphere (Fig. 4 of Hansen et al., 1981).

Although (13) provides a useful estimate of the (no feedback) surface temperature change resulting from a given radiative imbalance at the top of the atmosphere, it is a rough estimate because the radiation to space comes from a broad range of wavelengths and altitudes. In order to account for this spectral dependence, we used the 1-D radiative convective model for the following experiment. A flux of 1 W m^{-2} was arbitrarily added to the ocean surface, and the lapse rate, water vapor and other radiative constituents were kept fixed. The surface temperature increase at equilibrium was 0.29°C, implying

$$\Delta T_s(°C) \sim 0.29\ \Delta F(W\ m^{-2}) . \quad (14)$$

The coefficient in (14) is preferable to that in (13), for radiative perturbations which uniformly affect surface and atmospheric temperatures.

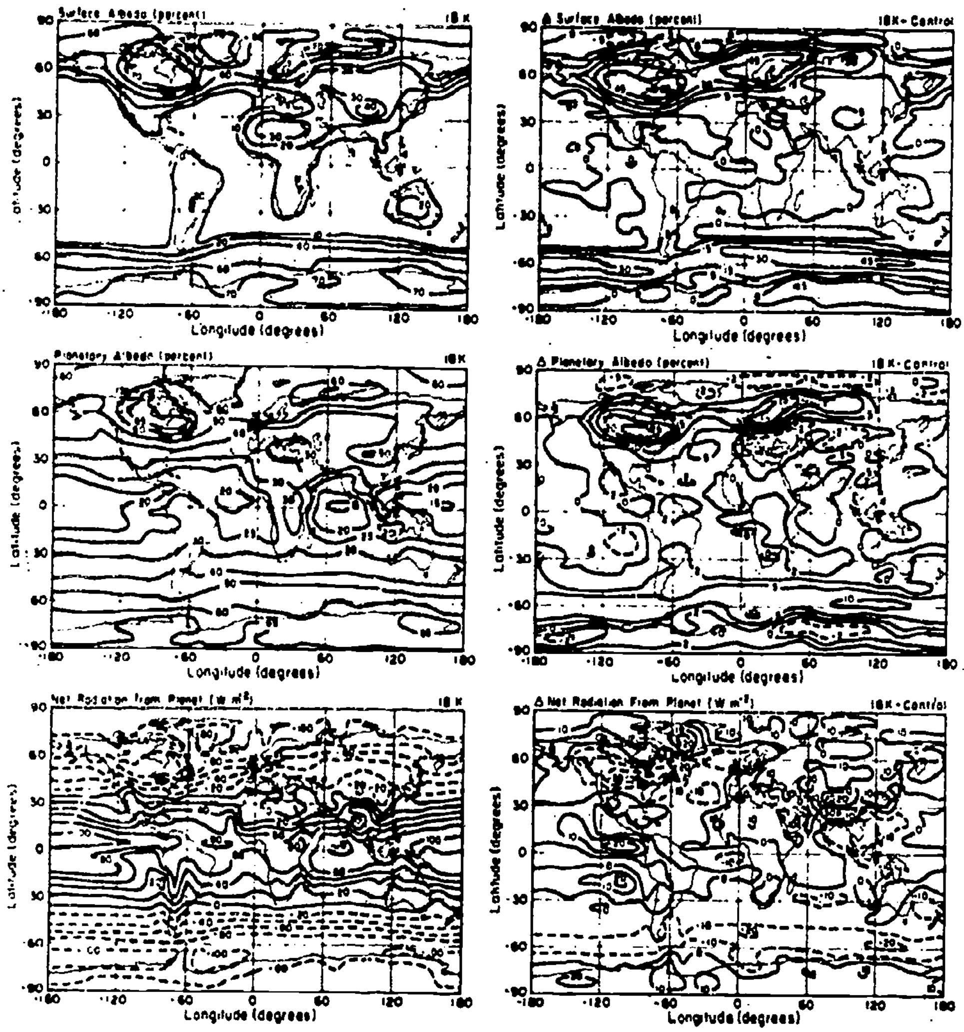

Fig. 10. Radiation quantities for the 18K simulation and differences with the control run. The control run is described in detail in paper 1.

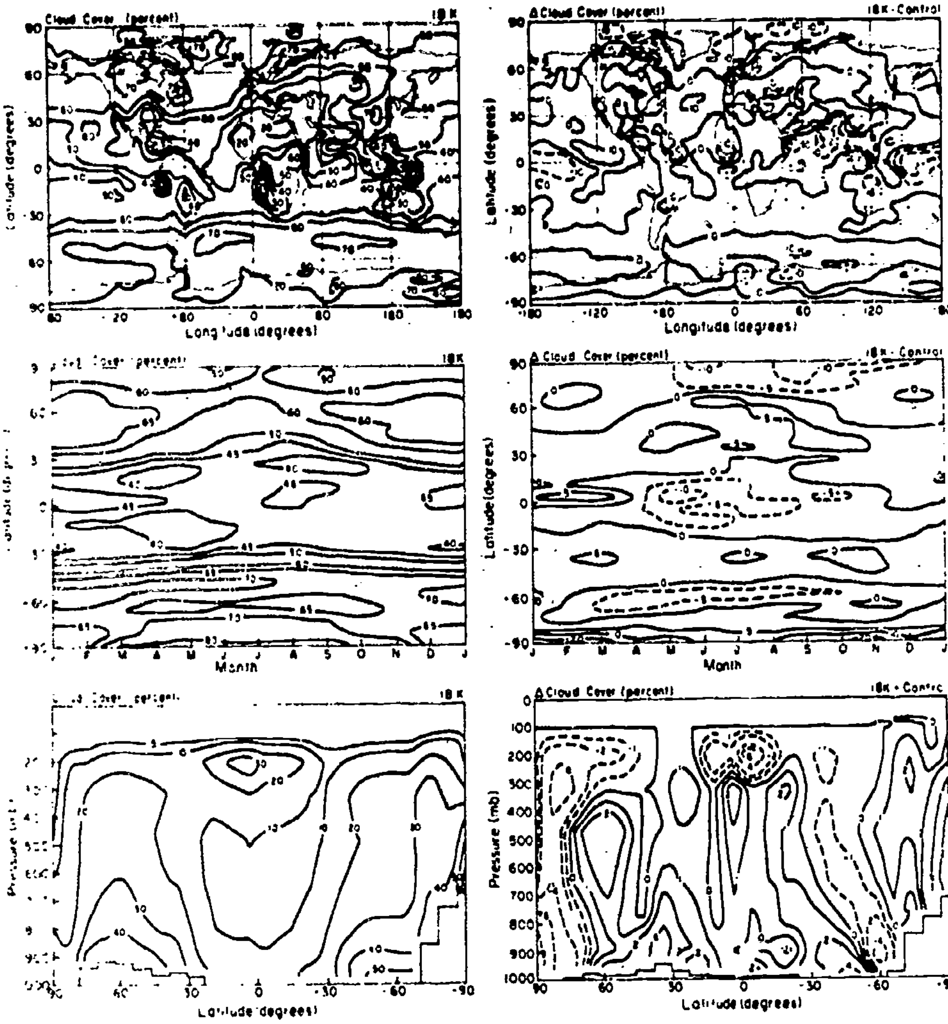

Fig. 11. Cloud cover for the 18K simulation and differences with the control run. The control run is described in detail in paper 1.

Water vapor and cloud feedbacks. Although we do not have measurements of the water vapor and cloud distribution for 18K, we can use experiment 8 to determine the combined water vapor/cloud feedback factor in our 3-D model for the 18K simulation. In this experiment the ocean surface temperature was arbitrarily decreased by 2°C everywhere. As shown in Table 3, the global mean surface temperature decreased by 2°C and the net radiation flux to space decreased by 2.7 W m^{-2}. Thus, with the sea ice and land ice fixed, the model sensitivity $\Delta T/\Delta F$ for the combined water vapor and cloud feedbacks is 0.78°C $(W/m^{-2})^{-1}$. If no feedbacks were allowed to operate, the sensitivity would be ~0.29°C $(W/m^2)^{-1}$, cf. equation (14). Thus, since the atmospheric feedbacks are the only ones allowed to operate in experiment 8, we infer that the combined water vapor and cloud feedback factor in our model for 18K is $f_{wc} \sim 2.6$ and $g_{wc} \sim 0.6$. This is practically the same as the combined water vapor and cloud feedbacks for the doubled CO_2 experiment [Table 1 and equation (12)].

Experiment 8 can be used to convert the flux imbalances at the top of the atmosphere in the other unsteered experiments in Table 3 to equilibrium surface temperature changes. Thus, if the ocean temperature were free to change and water vapor and clouds were the only operative feedbacks, a flux imbalance ΔF at the top of the atmosphere would vanish as the surface temperature changed by an amount $\Delta T = 0.78\ \Delta F$.

Sea ice and land ice feedbacks. Experiments 9 and 10, in which the 18K distributions of sea ice and land ice were replaced with today's distributions, show that both the sea ice and land ice changes made major contributions to the ice age cooling (Table 3). The CLIMAP sea ice and land ice distributions each affect the global ground albedo by ~0.02. Atmospheric shielding and zenith angle effects reduce the impact on planetary albedo to 0.006 for the sea ice change and 0.009 for the land ice change. The impact on the net radiation balance with space is between 1.5 and 2.0 W m^{-2} in each case, for these experiments in which the atmosphere was allowed to adjust to the changed sea ice and land ice.

The radiation imbalances in these experiments of the first type can be used to estimate the gain factors for these two feedback processes. Based on the conversion factor 0.78°C/(W m^{-2}), the flux imbalances in experiments 9 and 10 yield equilibrium surface temperature changes of $\Delta T_{sea\ ice}$ = 1.9K and $\Delta T_{land\ ice}$ = 2.3K. Since the feedback factor in these experiments is f_{wc} = 2.6, the radiative forcings produced by the sea ice and land ice changes in the absence of feedbacks are $\Delta T_{sea\ ice} = 1.9K/f_{wc} = 0.7K$ and $\Delta T_{land\ ice}$ = 0.9K, respectively. Thus the gain factors for sea ice and land ice changes, for the climate change from 18K to today, can be estimated as

$$g_{sea\ ice} \sim 0.7/\Delta T \sim 0.14\text{-}0.20$$
$$g_{land\ ice} \sim 0.9/\Delta T \sim 0.18\text{-}0.25 \qquad (15)$$

where ΔT is the change of global mean surface air temperature in °C between 18K and today. Experiment 7 yields ΔT = 3.6°C, but indications that CLIMAP low latitude ocean temperatures are too warm (see above) suggest $\Delta T \sim 5°C$; the range given for g refers to ΔT = 3.6-5°C.

In experiments 9* and 10* the 18K distributions of sea ice and land ice in experiment 1 were replaced with today's distributions, but only for diagnostic calculation of the planetary radiation balance; all other quantities in the diagnostic calculation were from experiment 7. Based on the radiative forcings computed at the top of the atmosphere and Eq. (13) we estimate the gain factors, $g_i = \Delta T_i/\Delta T$, for the sea ice and land ice changes to be

$$g_{sea\ ice} \sim \frac{0.27 \times 3.1}{\Delta T} \sim 0.17\text{-}0.23$$
$$g_{land\ ice} \sim \frac{0.27 \times 3.6}{\Delta T} \sim 0.19\text{-}0.27 \ . \qquad (16)$$

These gain factors include the effect of ice on thermal emission and planetary albedo. The fact that the gains estimated from (16) exceed those from (15) indicates that the emission from the added snow and ice surfaces on the average is from a somewhat higher temperature than the effective temperature, 255K.

The accuracy of these feedback gains depends primarily on the accuracy of the CLIMAP boundary conditions. Indeed, it is possible that the CLIMAP sea ice distribution is too extensive. Burckle et al. (1982), on the basis of satellite measurements of sea ice coverage, and present sediment distributions, suggest that the sediment boundaries which CLIMAP had assumed to be the summer sea ice limit in the Southern Hemisphere are in fact more representative of the spring sea ice limit. Experiments 11 and 11* test the effect of this reduced sea ice coverage. In experiment 1 the CLIMAP February and August sea ice coverage were used as the extremes and interpolated sinusoidally to other months. For experiments 11 and 11* the winter (August) coverage was left unchanged, but the CLIMAP Southern Hemisphere February coverage was used for the spring (November) with linear extrapolation to February, and linear interpolation between the February and August extremes.

Experiment 11* implies that the sea ice gain estimated in experiments 9 and 9* should be reduced by 15-20 percent, if the arguments of Burckle et al. (1982) are correct. Although

TABLE 3. Changes in planetary radiation balance in climate model experiments. The control run for experiments 7, 11, and 13 is climate model II documented in paper 1. σ is the standard deviation of the annual mean about the 5 year mean for this control run; standard deviations for the other control runs were of similar magnitude. Experiment 7 was run for 6 years, with the results averaged over the final 5 years. The other unstarred experiments were run for 4 years and averaged over the final 3 years. The starred experiments were run for 3 years and averaged over 3 years. T_s is surface air temperature, F net radiation at the top of the atmosphere, A_g ground albedo and A_p planetary albedo. Global values are shown, with the numbers in parenthesis being the results for the Northern Hemisphere and Southern Hemisphere respectively. Experiment 7', the control run for experiment 12, was identical to experiment 7 except that the Koppen vegetation of Fig. 12(a) was substituted for Matthews (1982) 1° x 1° vegetation used in model II.

Experiment	Description	Control Run	ΔT_s(°C)	$100 \times \Delta A_g$	$100 \times \Delta A_p$	ΔF ($W\ m^{-2}$)
7	18K boundary conditions	model II (paper 1)	-3.6(-4.6,-2.5)	4.1(5.0,3.1)	1.8(2.2,1.8)	-1.6(-0.1,-3.2)
8	ocean temperature reduced by 2°C	experiment 7	-2.0(-2.0,-2.8)	0.4(0.4,0.4)	0.5(0.5,0.5)	3.7(2.7,2.8)
9	today's sea ice	experiment 7	0.6(0.5,0.7)	-1.8(-0.9,-2.7)	-0.6(-0.3,-0.8)	1.7(0.6,2.8)
10	today's land ice	experiment 7	0.9(1.7,0.1)	-1.9(-3.6,-0.2)	-0.9(-1.3,-0.5)	1.8(2.4,1.4)
11	reduced 18K sea ice	model II (paper 1)	-3.5(-4.6,-2.4)	3.7(5.0,2.4)	1.8(2.2,1.4)	-1.4(0.1,-2.9)
12	18K vegetation	experiment 7'	-0.1(-0.3,0.0)	0.6(1.2,0.0)	0.3(0.5, 0.1)	-0.8(-1.4,-0.4)
13	modified 18K boundary conditions	model II (paper 1)	-3.7(-5.0,-2.4)	3.4(4.9,1.9)	1.7(2.2,1.3)	-2.1(-0.2,-3.8)
14	CO_2 (315→200 ppm)	experiment 7	-0.2(-0.3,-0.1)	0.1(0.1,0.1)	0.2(0.2,0.1)	-2.2(-2.3,-2.1)
9*	today's sea ice	experiment 7	-	-1.8(-0.8,-2.8)	-0.5(-0.4,-0.7)	3.1(2.0,4.3)
10*	today's land ice	experiment 7	-	-1.5(-2.7,-0.4)	-0.6(-1.1,0.0)	3.6(6.4,0.7)
11*	today's sea ice	experiment 11	-	-1.3(-0.9,-1.8)	-0.5(-0.4,-0.6)	2.8(1.8,3.3)
	$\sigma_{control}$		0.04(0.03,0.06)	0.05(0.07,0.03)	0.09(0.09,0.10)	0.3(0.3,0.4)

there is uncertainty about the true 18K sea ice distribution, it seems likely that the original CLIMAP data is somewhat an overestimate. On the basis of experiments 9, 9* and 11* our best estimate of the sea ice gain for the climate change from 18K to today is $g_{sea\ ice} \sim 0.15$ and thus a feedback factor $f_{sea\ ice} \sim 1.2$. This is larger than the snow/ice feedback obtained in the S_0 and CO_2 experiments. However, the area of the sea ice cover change is about twice as large in the 18K experiment (-18.4×10^6 km^2 for the annual mean with our revised CLIMAP sea ice) than in these other experiments (7.8×10^6 km^2, 9.2×10^6 km^2 and 14.8×10^6 km^2 in the S_0, CO_2 and alternate CO_2 experiments, respectively). Thus, the gains obtained from the ice age and the warmer climate experiments are consistent.

It also has been argued (DiLabio and Klassen, 1983) that the CLIMAP land ice cover is an overestimate, because the ice sheet peripheries probably did not all achieve maximum extent simultaneously. This possibility was recognized by the CLIMAP investigators, who therefore also presented a minimal extent ice sheet model for 18K (Denton and Hughes, 1981; CLIMAP, 1981). In this minimal ice model the area by which the ice sheets of 18K exceeded those of today is reduced to five-sixths of the value in the standard CLIMAP model. We conclude that the land ice gain for the climate change from 18K to today is 0.15-0.25. The corresponding feedback factor is 1.2-1.3.

<u>Vegetation feedback</u>. We also investigated the vegetation feedback, which Cess (1978) has estimated to provide a large positive feedback. We used the Koppen (1936) scheme, which relates annual and monthly mean temperature and rainfall to vegetation type, to infer expected global vegetation distributions for the GCM runs representing today's climate (model II in paper 1) and the 18K climate. The resulting vegetation distribution from the run with today's boundary conditions (Fig. 12a) suggests that the model and Koppen scheme can do a fair job of 'predicting' vegetation, in the case of today's climate for which the scheme was derived. Discrepancies with observed vegetation (Matthews, 1983) exist, e.g., there is too much rainforest on the east coast of Africa and too little boreal forest in central Asia, but the overall patterns are realistic.

The vegetation distribution obtained for 18K (Fig. 12b) from the Koppen scheme and our 18K experiment has more desert than today, less rainforest and less boreal forest. These changes are qualitatively consistent with empirical evidence of tropical aridity during the last glacial maximum based on a variety of paleoclimate indicators, such as pollen (Flenley, 1979), fauna (Vuilleumier, 1971), geomorphology (Sarnthein, 1978) and lake levels (Street and Grove, 1979). However, the magnitude of the desert and rainforest changes is smaller than suggested by the

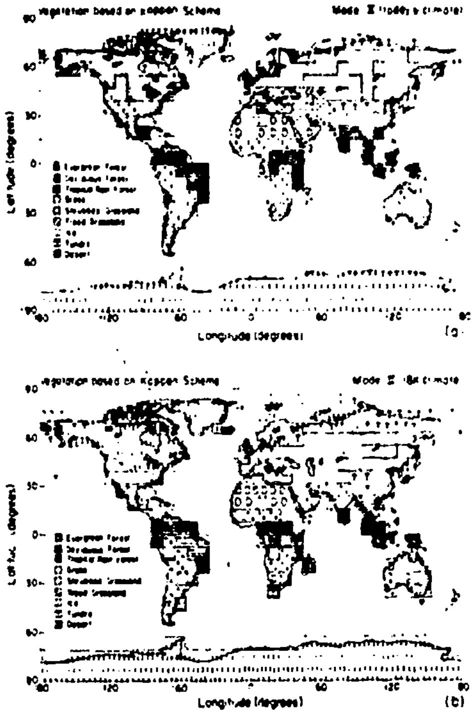

Fig. 12. Vegetation types (for gridboxes with more than 30 percent land) inferred from 3-D model simulations and the Koppen (1936) scheme, which relates annual and monthly mean temperature and precipitation to vegetation type. (a) is the control run for today's climate (paper 1), while (b) is the 18K simulation (experiment 7).

paleoclimate evidence. The smaller changes may result from (a) the CLIMAP tropical ocean temperatures being too warm, as discussed above, which would tend to cause an overestimate of rainforest and underestimate of desert area; (b) the lower atmospheric CO_2 abundance of 18K (Shackleton et al., 1983), since CO_2 'fertilization' effects are not included in the Koppen scheme.

In experiment 12 today's vegetation was replaced with the Koppen 18K vegetation (Fig. 12b). The land, land ice and other boundary conditions were identical to those in the control run. In this experiment the modified vegetation directly affects the planetary albedo and also indirectly affects it through the masking depth for snow (paper I). The 18K Koppen vegetation of Fig. 12b increased the global ground albedo by 0.006 and the planetary albedo by 0.003 (Table 3) and left a flux imbalance of -0.9 W m^{-2} at the top of the atmosphere. Based on the same analysis as for ice above, the no-feedback temperature change due to vegetation is 0.3°C, yielding $g_{vegetation}$ = 0.06-0.08. Because of the imprecisions in the Koppen 18K vegetation, we broaden the estimated gain to $g_{vegetation}$ = 0.05-0.09, and thus $f_{vegetation}$ = 1.05-1.1. Examination of global maps shows that the greatest impact of the changed vegetation was the replacement of European and Asian evergreen forests with tundra and grassland; the greatly reduced masking depths produced annual ground albedo increases of 0.1 or more over large areas, with the largest changes in spring. For reasons stated above, we also examined an 18K run with ocean temperatures reduced by 2°C; this reduced the number of gridboxes with rainforest from 10 to 5 in South America and from 7 to 2 in Africa, compared to Fig. 12b, in better agreement with paleoclimate evidence cited above. This additional vegetation change did not significantly change the global albedo or flux at the top of the atmosphere.

We conclude that the vegetation feedback factor between 18K and today is $f_{vegetation}$ ~ 1.05-1.1. This is much smaller than suggested by Cess (1978), but consistent with the analysis of Dickinson (1984). We find a somewhat larger feedback than Dickinson obtained, 0.003 change of planetary albedo compared to his 0.002, apparently due to the change of vegetation masking of snow-covered ground.

18K Radiation Balance

The simulated 18K climate (experiment 7) is close to radiation balance, the imbalance (Table 3) being 1.6 W m^{-2} at the top of the atmosphere, compared to the control run (model II) for today's climate. This imbalance is small compared to the amount of solar energy absorbed by the planet (~240 W m^{-2}). However, in reality even more precise radiation balance must have existed averaged over sufficient time, because the ice age lasted much longer than the thermal relaxation time of the ocean. (Melting the ice sheets in 10K years would require a global mean imbalance of only ~0.1 W m^{-2}.) Although the model calculations contain imprecisions comparable in magnitude to the radiation imbalance, we expect these to be largely cancelled by the procedure of differencing with the control run. This type of study should become a powerful tool in the future, as the accuracy of the reconstructed ice age boundary conditions improves and as the climate models become more realistic.

Taken at face value, the radiation imbalance in the 18K experiment 7 implies an imprecision in either some of the assumed boundary conditions for 18K or in the climate model sensitivity. The sense of the imbalance is such that the planet would cool further (to -4.9°C, based on the ΔF in Table 3), if the ocean temperature were computed rather than specified. Before studying this imbalance further, we make three modifications to the 18K simulation. First, the Southern Hemisphere sea ice cover is reduced as discussed above; this reduces the radiation imbalance. Second, the vegetation is replaced by the 18K vegetation of Fig. 12b; this slightly reduces the radiation imbalance. Third, the amount of atmospheric CO_2 is reduced in accord with evidence (Neftel et al., 1982) that the 18K CO_2 amount was only ~200 ppm; this significantly aggravates the radiation imbalance.

These three changes are all included in experiment 13, the sea ice and vegetation changes being those tested in experiments 11 and 12. The CO_2 decrease was 75 ppm from the control run value of 315 ppm; this is equivalent to the change from an estimated preindustrial abundance of 270 ppm to an ice age abundance of ~200 ppm. With these changes the radiation imbalance with space becomes 2.1 W m^{-2}. This imbalance would carry the surface temperature to -5.3°C if the constraint on ocean temperature were released.

Two principal candidates we can identify for redressing the 18K radiation imbalance are the CLIMAP sea surface temperatures and the cloud feedback in the climate model. The imbalance is removed if the CLIMAP ocean temperature is 1.5°C too warm (experiment 8, Table 3). The possibility that the CLIMAP sea surface temperatures may be too warm is suggested by the discussion above. The imbalance is also removed if it is assumed that clouds provide no feedback, rather than the positive feedback which they cause in this model; this conclusion is based on the estimate that the clouds cause 30-40 percent of the combined water vapor/cloud feedback (experiment 8), as is the case in the S_0 and CO_2 experiments.

One plausible solution is the combination of a reduction of low latitude ocean temperature by ~1°C and a cloud feedback factor between 1 and 1.3. An alternative is a reduction of low latitude ocean temperature by ~1°C and a greater value for the 18K CO_2 abundance; indeed, recent analyses of Shackleton et al. (1983) suggest a mean 18K CO_2 abundance ~240 ppm. It is also possible that there were other presently unsuspected changes of boundary conditions.

There are presently too many uncertainties in the climate boundary conditions and climate model to permit identification of the cause of the radiation imbalance in the 18K simulation. However, as the boundary conditions and climate models become more accurate, this approach should yield valuable checks on paleoclimate data and climate models. In the meantime, the data permits some general conclusions about the strength of climate feedback processes.

Conclusions from 18K Experiments

The above calculations suggest the following major contributions to the global cooling at 18K, as shown schematically in Fig. 13:

$$\Delta T_{water\ vapor\ +\ clouds} \equiv \Delta T_{wc} \sim 1.4\text{-}2.2°C$$

$$\Delta T_{land\ ice} \equiv \Delta T_l \sim 0.7\text{-}0.8°C$$

$$\Delta T_{sea\ ice} \equiv \Delta T_s \sim 0.6\text{-}0.7°C \qquad (17)$$

$$\Delta T_{CO_2} \sim 0.3\text{-}0.6°C$$

$$\Delta T_{vegetation} \equiv \Delta T_v \sim 0.2°C$$

These estimates are the product of the gain for each process and the total cooling at 18K. But note that the uncertainty in the total ΔT cancels in obtaining ΔT_l, ΔT_s, ΔT_{CO_2} and ΔT_v; thus these ΔT_i are more fundamental and accurate than the corresponding g_i. The ΔT_i represent the isolated radiative forcings, which can be computed accurately, for the assumed changes in these radiative constituents between 18K and today. ΔT_{wc} = 2.2°C is obtained from experiment 8 which yielded g_{wc} ~ 0.8. The cloud portion of ΔT_{wc} is uncertain because of the rudimentary state of cloud modeling; however even with no cloud feedback the water vapor contribution (~1.4°C) is a large part of the total ice age cooling. ΔT_l = 0.8°C is based on the CLIMAP maximal ice sheet extent; it is ~0.7°C for the minimal extent mode. ΔT_s = 0.7°C is based on CLIMAP sea ice; it is 0.6°C with the reduced sea ice cover in the Southern Hemisphere in experiments 11 and 11*. ΔT_{CO_2} = 0.6°C refers to a CO_2 change from 200 ppm (at 18K) to 300 ppm (at say 1900); this is reduced to 0.3°C if the CO_2 amount was 225 ppm at 18K and 275 ppm at 1800.

The sum of the temperature contributions in Fig. 13 slightly exceeds the computed cooling ΔT = 3.7°C at 18K. This is a restatement of the radiation imbalance which exists in the model when the CLIMAP boundary conditions are used with ΔCO_2 of 50-100 ppm. If the model ocean temperature were allowed to change to achieve radiation balance, it would balance at a global mean 18K cooling of ~5.3°C [model sensitivity = 0.76°C/(W m^{-2})]. We conclude that either the CLIMAP 18K ocean temperatures are too warm by ~1.5°C or we have overestimated one or more of the contributions to the 18K cooling in (17).

It is apparent from Fig. 13 that feedback processes account for most of the 18K cooling. The water vapor, cloud and sea ice contributions represent at least half of the total cooling. On long time scales the land ice portion of the cooling also may be regarded as a feedback, though it operates on a very regional scale and may be a complex function of a variety of factors such as the position of land areas, ocean currents and the meteorological situation. Even the CO_2 portion of the cooling, or at least part of it, may be a feedback, i.e., in response to the change of climate.

Variations in the amount of absorbed solar radiation due to Milankovitch (earth orbital) changes in the seasonal and latitudinal distributions of solar irradiance, which occur on time scales of several thousand years, can provide a global mean forcing of up to a few tenths of a degree. In view of the strength of the climate feedbacks, it is plausible for the Milankovitch and CO_2 forcings to 'drive' glacial to interglacial climate variations. However, discussion of the sequence of causes and mechanisms of glacial to interglacial climate change is beyond the scope of this paper.

We can use the contributions to the 18K cooling summarized in Fig. 13 to obtain an empirical estimate of the climate feedback factor due to the processes operating on 10-100 year time scales, taking the land ice, CO_2 and vegetation changes from 18K to today as slow (or at least specified). The global mean radiative forcing due to the difference in 18K and today's orbital parameters is negligible compared to the other forcing summarized in Fig. 13. The feedback factor for the fast (water vapor, clouds, sea ice) processes is

$$f(\text{fast processes}) = \frac{\Delta T(\text{total})}{\Delta T(\text{slow processes})} \qquad (18)$$

ΔT(total) is ~3.7°C for the CLIMAP boundary conditions, but may be ~5°C, if CLIMAP low latitude ocean temperatures are 1-2°C too warm. Using the nominal CLIMAP boundary conditions and intermediate estimates for ΔT_l ~ 0.4, ΔT_{CO_2} ~ 0.45 and ΔT_v ~ 0.3, yields f(fast processes) ~ 2.4. Using ΔT(total) ~ 5°C and these nominal radiative forcings yields f ~ 3.2. Allowing for the more extreme combinations of the forcings and ΔT(total), we conclude that

$$f(\text{fast processes}) \sim 2\text{-}4 \qquad (19)$$

This feedback factor, f ~ 2-4, corresponds to a climate sensitivity of 2.5-5°C for doubled CO_2. Note that this result is independent of our climate model sensitivity: it depends on the total ΔT at 18K (fixed by CLIMAP) and on the assumption that land ice, CO_2 and vegetation are the only major slowly changing boundary conditions. Of course some vegetation and CO_2 feedbacks may occur in less than 100 years but for projecting future climate it is normal to take these as specified boundary conditions.

Finally, note that a given sensitivity for fast feedback processes, say 4°C for doubled CO_2, does not mean that the climate necessarily would warm by 4°C in 10 or even 100 years. Although water vapor, cloud and sea ice feedbacks respond rapidly to climate change, the speed of the climate response to a changed forcing depends on

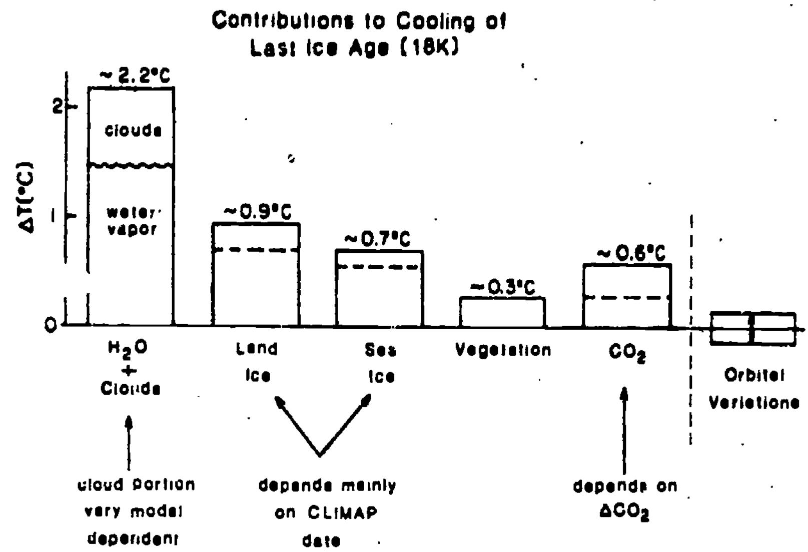

Fig. 13. Contributions to the global mean temperature difference between the Wisconsin ice age and today's climate as evaluated with a 3-D climate model and assumed boundary conditions. The cloud and water vapor portions were not separated, but based on other 3-D experiments the cloud part is estimated as 30-40 percent of their sum. The dashed line for land ice refers to the 'minimal extent' model of CLIMAP, and the dashed line for sea ice refers to the reduced sea ice cover discussed in the text. The solid line for CO_2 refers to ΔCO_2 ~ 100 ppm (300 ppm → 200 ppm) and the dashed line to ΔCO_2 ~ 50 ppm.

the rate at which heat is supplied to the ocean and on transport processes in the ocean.

Transient Response

Surface Response Time

The time required for the surface temperature to approach its new equilibrium value in response to a change in climate forcing depends on the feedback factor, f. The following example helps clarify this relationship.

Let the solar flux absorbed by a simple blackbody planet ($f \equiv 1$) change suddenly from $F_0 = \sigma T_0^4$ to $F_0 + \Delta F \equiv \sigma T_1^4$, with $\Delta F << F_0$. The rate of change of heat in the climate system is

$$\frac{d(cT)}{dt} = \sigma T_1^4 - \sigma T^4 \sim -4\sigma T_0^3(T - T_1) \quad (20)$$

where c is the heat capacity per unit area and T is the time varying temperature. Since $T_1 - T_0 << T_0$, the solution is

$$T - T_0 = (T_1 - T_0)[1 - \exp(-t/\tau_b)] \quad (21)$$

where the blackbody no-feedback e-folding time is

$$\tau_b = c/4\sigma T_0^3 \ . \quad (22)$$

For a planet with effective temperature 255 K and heat capacity provided by 63m of water (as in our 3-D experiments), τ_b is approximately 2.2 years. Thus, this planet with $f = 1$ exponentially approaches its new equilibrium temperature with e-folding time 2.2 years.

Feedbacks modify the response time since they come into play only gradually as the warming occurs, the initial flux of heat into the ocean being independent of feedbacks. It is apparent that the actual e-folding time for a simple mixed layer heat capacity is

$$\tau = f\tau_b \quad (23)$$

An analytic derivation of (23) is given in Appendix A. The proportionality of the mixed layer response time to f is apparent in Fig. 3; the e-folding time for that model, which has f ~ 2.5 and a 63m mixed layer, is ~8 years.

The 63m mixed layer depth in our 3-D experiments was chosen as the minimum needed to obtain a realistic seasonal cycle of temperature, thus minimizing computer time needed to reach equilibrium. However, the global-mean annual-maximum mixed layer depth from our compilation of observations (see above) is ~110m, and thus the isolated ocean mixed layer has a thermal response time of ~15 years if the climate sensitivity is 4°C for doubled CO_2. Even if the climate sensitivity is 2-3°C for doubled CO_2, the (isolated) mixed layer response time is about 10 years.

In order to determine the effect of deep ocean layers on the surface response time, it is useful to express the heat flux into the ocean as a function of the difference between current surface temperature and the equilibrium temperature for current atmospheric composition. In Appendix A we show that

$$F(W\ m^{-2}) = \frac{F_0}{\Delta T_{eq}(2*CO_2)} (\Delta T_{eq} - \Delta T) \qquad (24)$$

where ΔT is the ocean surface temperature departure from an arbitrary reference state and ΔT_{eq} is the equilibrium temperature departure for current atmospheric composition. $\Delta T_{eq}(2*CO_2)$ is the equilibrium sensitivity for doubled CO_2; for our 3-D climate model it is 4.2°C. F_0 is the flux into the ocean in the model when CO_2 is doubled and the stratospheric temperature has equilibrated; our 3-D model yields F_0 = 4.3 W m^{-2}.

The long response time of the isolated mixed layer allows a portion of the thermal inertia of the deeper ocean to come into play in delaying surface temperature equilibrium. Exchange between the mixed layer and deeper ocean occurs by means of convective overturning in the North Atlantic and Antarctic oceans and principally by nearly horizontal motion along isopycnal (constant density) surfaces at lower latitudes. Realistic modeling of heat perturbations is thus rather complex, especially since changes of surface heating (and other climate variables) may alter the ocean mixing. However, we can obtain a crude estimate for the surface response time by assuming that small positive heat perturbations behave as a passive tracer; numerical experiments of Bryan et al (1984) support this assumption. Measurements of transient tracers in the ocean, such as the tritium sprinkled on the ocean surface by atmospheric atomic testing, provide a qualitative indication of the rate of exchange of water between the mixed layer and the upper thermocline (see, e.g., Ostlund et al., 1976).

We estimate an effective thermocline diffusion coefficient (k) at each GEOSECS measurement station from the criterion that the modeled and observed penetration depths (Broecker et al., 1980) be equal at each station. The resulting diffusion coefficients are well correlated (inversely) with the stability at the base of the winter mixed layer (Fig. 14). In particular, we find a correlation coefficient of 0.85 between k and $1/N^4$, where N is the Brunt-Vaisala frequency at the base of the mixed layer. The global distribution of N^2 was obtained from the ocean data set of Levitus (1982).

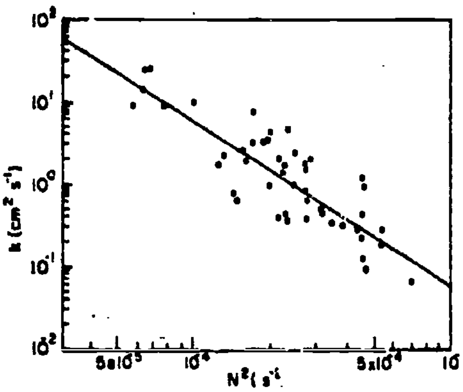

Fig. 14. Relationship between the effective diffusion coefficient (k) and the stability (N^2, where N is the Brunt-Vaisala frequency) at the base of the winter mixed layer for the GEOSECS tritium stations north of 20°S. The regression line fit (Eq. 25) has correlation coefficient 0.85 with the points for individual stations.

The empirical relation between k and stability,

$$k = 3 \times 10^{-8}/N^4, \qquad (25)$$

and the global ocean data set of Levitus (1982) yield the global distribution of k at the base of the mixed layer shown in Fig. 15a. There is a low rate of exchange (k < 0.2 cm^2 s^{-1}) in the eastern equatorial Pacific where upwelling and the resulting high stability at the base of the mixed layer inhibit vertical mixing, but rapid exchange (k > 10 cm^2 s^{-1}) in the Greenland - Norwegian Sea area of convective overturning.

The e-folding time for the mixed layer temperature (time to reach 63 percent of the equilibrium response) is shown in Fig. 15b. This is calculated from the geographically varying k and annual-maximum mixed layer depth, assuming a sudden doubling of CO_2 and an equilibrium sensitivity of 4.2°C everywhere. The (63 percent) response time is about 20-30 years at low latitudes, where the shallow mixed layer and small k allow the mixed layer temperatures to come into equilibrium relatively quickly. At high latitudes, where the deep winter mixed layer and large k result in a larger thermal inertia, the response

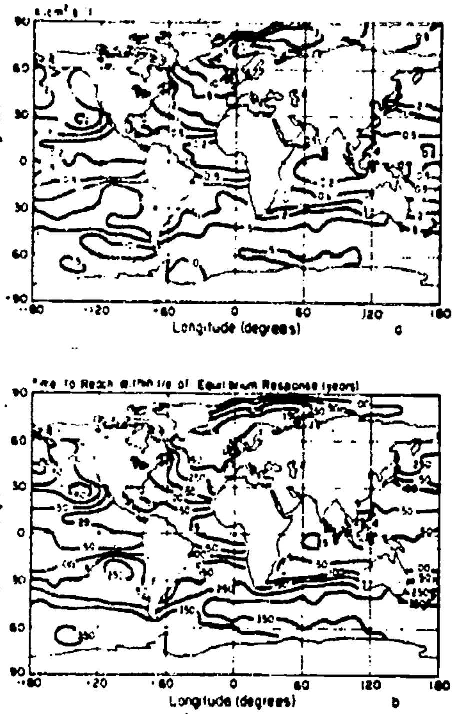

Fig. 15. (a) Geographic distribution of effective thermocline diffusion coefficient, k ($cm^2 s^{-1}$). k is derived from Eq. 25 and the global distribution of N^2, the latter obtained from the ocean data of Levitus (1982). (b) Geographic distribution of the 63 percent response time for surface temperature response to doubled CO_2 in the atmosphere. Only geographic variability of k and mixed layer depth are accounted for. $\Delta T_{eq}(2{*}CO_2)$ is taken as 4.2°C everywhere. The flux into the ocean is from Eq. (24).

time is about 200-400 years. The time for the global area-weighted mixed layer temperature to reach 63 percent of its equilibrium response is 124 years.

We estimate an equivalent k for use in a global 1-D model by choosing that value of k which fits the global (area-weighted) mean perturbation of the mixed layer temperature as a function of time obtained with the above calculation in which k and mixed layer depth vary geographically. We find that $k \sim 1\ cm^2\ s^{-1}$ provides a reasonable global

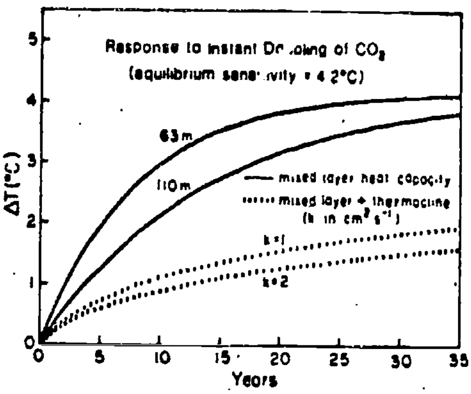

Fig. 16. Transient response to step function doubling of atmospheric CO_2 from 315 ppm to 630 ppm, computed from (24) with three representations of the ocean. The 63 m mixed layer corresponds to the mean mixed layer depth in the 3-D experiments, 110 m is the global-mean annual maximum mixed layer depth obtained from global ocean data. The curves including diffusion beneath the mixed layer are not exponentials (Appendix A).

fit to the area-weighted local calculations for either a step function change of CO_2 or exponentially increasing CO_2 amount. Other analyses of the tracer data yield empirical values of 1-2 cm^2 s^{-1} for the effective rate of exchange between the mixed layer and deeper ocean (Broecker et al., 1980).

The delay time due to the ocean thermal inertia is graphically displayed in Fig. 16. Equation (24) provides a good approximation of the time dependence of the heat flux into the ocean in our 3-D climate experiment with doubled CO_2, as shown by comparison of Figs. 3b and 16. Note that in our calculation with a mixed layer depth of 110 m, k = 1 $cm^2\ s^{-1}$, and ΔT_{eq} = 4.2°C. The time required to reach a response of 2.65°C is 102 years. This is in rough agreement with the 124 years obtained above with the 3-D calculation.

The ocean delay time is proportional to f for an isolated mixed layer (eq. (23) and Appendix A), but depends more strongly on f if mixing into the deeper ocean is included. Our 1-D calculation with k = 1 $cm^2\ s^{-1}$ and mixed layer depth 110 m yields an e-folding time of 55 years for ΔT_{eq} = 3°C and 27 years for ΔT_{eq} = 2°C. Thus our ocean response time is consistent with that of Bryan et al. (1982), who obtained a response time of about 25 years for a climate model with sensitivity ~2°C for doubled CO_2.

Although our calculations were made with a simple diffusion model, the conclusion that the ocean surface temperature response time is highly nonlinear in ΔT_{eq} (or f) is clearly more general. The surface response time increases faster than linearly with f when the deeper ocean is included, because as f increases greater ocean depths come into play. Thus more realistic modeling of ocean transport processes should not modify these conclusions for small climate perturbations.

Our calculations of ocean response time neglect ocean circulation feedbacks on climate. The relationship between k and stability, equation (25), provides one way to examine the temperature feedback. By using that relation with our 1-D ocean diffusion model, we find that the time required to reach a given transient response is decreased, typically by several percent. Real ocean transports may be more sensitive to surface warming, as well as to related mechanisms such as melting of sea ice and ice sheets and changing winds, precipitation and evaporation. It is easy to construct scenarios in which the ocean feedbacks are much greater, especially in the areas of deep water formation, but not enough information is available for reliable calculation of ocean/climate feedbacks.

Finally, we note that the ocean surface thermal response time reported in the literature generally has been 8-25 years (Hunt and Wells, 1979; Hoffert et al., 1980; Cess and Goldenberg, 1981; Schneider and Thompson, 1981; Bryan et al., 1982). The 3-D ocean model result of Bryan et al. is consistent with our model when we employ a climate sensitivity of 2°C for doubled CO_2, as noted above. The discrepancy between our model response time and that of the other models arises from both the climate sensitivities employed and the choice of ocean model parameters. Key parameters are: mixed layer depth (we use 110m since any depth mixed during the year should be included), rate of exchange with deeper ocean (we use diffusion with $k = 1\ cm^2\ s^{-1}$, the minimum global value suggested by transient tracers, cf., Broecker et al., 1980) and the atmosphere-ocean heat flux (we use (24) which has initial value 4.3 $W\ m^{-2}$ over the ocean area for doubled CO_2 and is consistent with other 3-D models). Obviously the use of a 1-D box-diffusion model is a gross oversimplification of ocean transports. As an intermediate step between this and a 3-D ocean general circulation model, it may be valuable to study the problem with a model which ventilates the thermocline by means of transport along isopycnal surfaces. The agreement between the results from the 3-D ocean model of Bryan et al. and our model with a similar climate sensitivity suggests that our approach yields a response time of the correct order.

Impact on Empirically-Derived Climate Sensitivity

The delay in surface temperature response due to the ocean must be included if one attempts to deduce climate sensitivity from empirical data on time scales of order 10^2 years or less. Furthermore, in such an analysis it must be recognized that the lag caused by the ocean is not a constant, independent of climate sensitivity.

We computed the expected warming due to increase of CO_2 between 1850 and 1980 as a function of the equilibrium climate sensitivity. Results are shown in Fig. 17a for five choices of the 1850 CO_2 abundance (270±20 ppm), with CO_2 increasing linearly to 315 ppm in 1958 and then based on Keeling et al. (1982) measurments to 338 ppm in 1980. For simplicity a one-dimensional ocean was employed with mixed layer depth 110m and $k = 1\ cm^2\ s^{-1}$. However, we obtained a practically identical graph when we used a simple three-dimensional ocean with the mixed layer depth varying geographically according to the data of Levitus (1982) and k varying as in Fig. 15a.

Use of Fig. 17a is as follows. If we take 270 ppm as the 1850 CO_2 abundance (WMO, 1983) and assume that the estimated global warming of 0.5°C between 1850 and 1980 (CDAC, 1983) was due to the CO_2 growth, the implied climate sensitivity is 4°C for doubled CO_2 (f = 3-4). Results for other choices of the 1850 CO_2 abundance or global warming can be read from the figure.

Undoubtedly some other greenhouse gases also have increased in the past 130 years. Chlorofluorocarbons, for example, are of recent anthropogenic origin. CH_4 and N_2O are presently increasing at rates of 1-2 percent yr^{-1} and 0.2-0.3 percent per yr^{-1}, respectively (Ehhalt, et al., 1983; Weiss, 1981; CDAC, 1983). We estimate the influence of these gases on the empirical climate sensitivity by using the trace gas scenarios in Table 4. Although the CH_4 and N_2O histories are uncertain, the chlorofluorocarbons provide most of the non-CO_2 greenhouse effect, at least in the past 10-20 years (Lacis et al., 1981), and their release rates are known. CH_4 may have increased slowly for the past several hundred years (Craig and Chou, 1982), but the reported rate of increase would not affect the results much. O_3 is also a potent greenhouse gas, but information on its past history is not adequate to permit its affect to be included.

The climate sensitivity implied by the assumed global warming since 1850, including the effect of trace gases in addition to CO_2, is shown in Fig. 17b. If the 1850 CO_2 abundance was 270±10 ppm, as concluded by WMO (1983), a warming of 0.5°C requires a climate sensitivity 2.5-5°C for doubled CO_2. The range for the implied climate sensitivity increases if uncertainty in the amount of warming is also included. For example, a warming of 0.4-0.6°C and an 1850 CO_2 abundance of 270±10 ppm yield a climate sensitivity of 2-7°C.

Although other climate forcings, such as volcanic aerosols and solar irradiance, may affect this analysis, we do not have information adequate to establish substantially different magnitudes of these forcings prior to and subsequent to 1850.

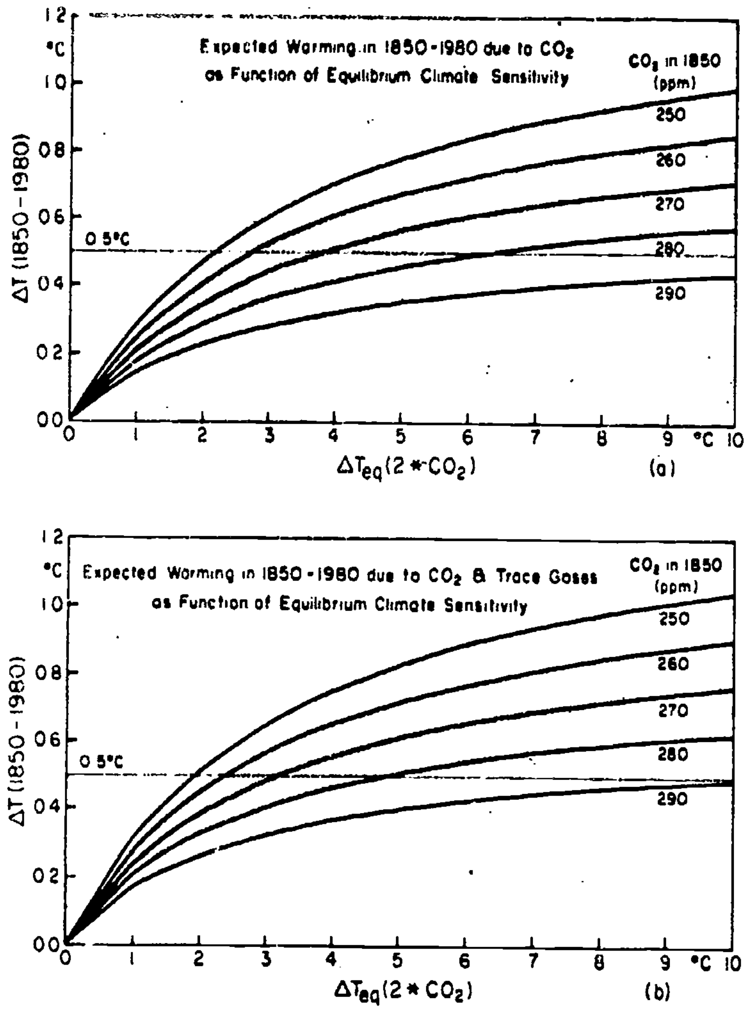

Fig. 17. Computed global warming between 1850 and 1980 as a function of the equilibrium climate sensitivity for doubled CO_2 (315 ppm → 630 ppm), $\Delta T_{eq}(2*CO_2)$. Results are shown for five values of the assumed abundance of CO_2 in 1850; the shaded area covers the range 270±10 ppm recommended by WMO (1983). (a) includes only CO_2 growth, while (b) also includes the trace gas growths of Table 4. In all cases CO_2 increases linearly from the 1850 abundance to 315 ppm in 1958 and then according to measurements of Keeling et al. (1982).

TABLE 4. Trace gas abundances employed in our calculations of the transient climate response for Figs. 17b and 18. CO_2 increases linearly for 1850-1958 and as observed by Keeling et al. (1982) for 1958-1980; ΔCO_2 increases about 2 percent yr^{-1} in the future. The chlorofluorocarbon abundances are based on estimated release rates to date, 150 year and 75 year lifetimes for CCl_2F_2 and CCl_3F, respectively, and constant future emissions at the mean release rate for 1971-1980. The CH_4 increase is about 1 percent yr^{-1} for 1970-1980 and 1.5 percent yr^{-1} after 1980. The N_2O increase is 0.2 percent yr^{-1} for 1970-1980 and 0.3 percent yr^{-1} after 1980.

Date	CO_2 (ppm)	CCl_2F_2 (ppt)	CCl_3F (ppt)	CH_4 (ppb)	N_2O (ppb)
1850	270	0	0	1400	295
1900	291	0	0	1400	295
1950	312	7	1	1400	295
1960	317	33	11	1416	295
1970	326	126	62	1500	295
1980	338	308	178	1650	301
1990	353	479	280	1815	307
2000	372	638	369	1996	313
2010	396	797	447	2196	320

The climate sensitivity we have inferred is larger than obtained by CDAC (1983) from analysis of the same time period (1850-1980) with the same assumed temperature rise. The chief reason is that CDAC did not account for the dependence of the ocean response time on climate sensitivity [equation (23) and Appendix A]. Their choice of a 15 year response time, independent of ΔT_{eq} or f, biased their result to low sensitivities.

We conclude that the commonly assumed empirical temperature increase for the period 1850-1980 (0.5°C) suggests a climate sensitivity of 2.5-5°C (f≈2-4) for doubled CO_2. The significance of this conclusion is limited by uncertainties in past atmospheric composition, the true global mean temperature change and its cause, and the rate at which the ocean takes up heat. However, knowledge of these factors may improve in the future, which will make this a powerful technique for investigating climate sensitivity.

Growing Gap Between Current and Equilibrium Climate

One implication of the long surface temperature response time is that our current climate may be substantially out of equilibrium with current atmospheric composition, as a result of the growth of atmospheric CO_2 and trace gases during recent decades. For example, in the last 25 years CO_2 increased from 315 ppm to 340 ppm and the chlorofluorocarbons from near zero to their present abundance. Since the growth rates increased during the period, the gas added during the past 25 years has been present on the average about 10 years. 10 years is short compared to the surface temperature response time, even if the climate sensitivity is only 2.5°C for doubled CO_2.

We illustrate the magnitude of this disequilibrium by making some calculations with the 1-D model specified to give the climate sensitivity of our 3-D model, 4.2°C for doubled CO_2, and with the changing atmospheric composition of Table 4. Fig. 18 shows the modeled surface temperature during the past century (1) for instant equilibrium with changing atmospheric composition, (2) with thermal lag due to the mixed layer included, and (3) with the thermocline's heat capacity included via eddy diffusion.

We infer that there is a large and growing gap between current climate and the equilibrium climate for current atmospheric composition. Based on the estimate in Fig. 18, we already have in the pipeline a future additional warming of almost 1°C, even if CO_2 and trace gases cease to increase at this time. A warming of this magnitude will elevate global mean temperature to a level at least comparable to that of the Altithermal (NAS, 1975, adapted in Fig. 1 of Hansen et al., 1984) about 6,000 years ago, the warmest period in the past 100,000 years.

The rate of warming computed after 1970 is much greater than in 1850-1980. This is because (1) ΔCO_2 is ~0.4 ppm yr^{-1} in 1850-1960, but >1 ppm yr^{-1} after 1970, and (2) trace gases, especially chlorofluorocarbons, add substantially to the warming after 1970. The surface warming computed for the period 1970-1990 is ~0.25°C; this is almost twice the standard deviation of the 5-year-smoothed global temperature (Hansen et al., 1981). But note that the equilibrium temperature increases by 0.75°C in the period 1970-1990, if the climate sensitivity is ~4°C for doubled CO_2. Thus our calculations indicate that the gap between current climate and the equilibrium climate for current atmospheric composition may grow rapidly in the immediate future, if greenhouse gases continue to increase at or near present rates.

As this gap grows, is it possible that a point will be reached at which the current climate "jumps" to the equilibrium climate? If exchange between the mixed layer and deeper ocean were reduced greatly, the equilibrium climate could be approached in as little as 10-20 years, the relaxation time of the mixed layer. Indeed, the stabi-

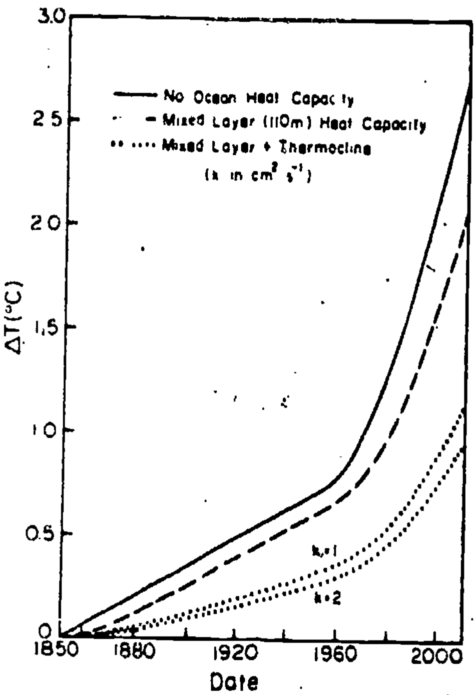

Fig. 18. Global mean warming computed for the CO_2 and trace gas scenarios in Table 4.

lity of the upper ocean layers seems likely to increase as the greenhouse warming heats the ocean surface, especially if the warming leads to an increased melting of ice which adds fresh water to the mixed layer. Regions of deep-water formation, such as the North Atlantic Ocean, may be particularly sensitive to changes in surface climate. However, it is difficult to predict the net effect of greenhouse warming on ocean mixing, because changes of precipitation, evaporation and atmospheric winds, in addition to temperature, will affect ocean mixing and transport. If possible, it would be useful to examine paleoclimate records for evidence of sudden climate warmings on 10-20 year time scales, since there may have been cases in the past when the long thermal response time of the ocean allowed gaps between actual and equilibrium climates to build up.

Even if it does not lead to a dramatic jump to a new climate state, the gap between current climate and the equilibrium climate for current atmospheric composition may have important climatic effects as it grows larger. For example, it seems possible that in the summer, when zonal winds are weak, continental regions may tend partly toward their equilibrium climate, thus causing a relatively greater warming in that season. Also, in examining the climate effects of recent and future large volcanoes, such as the 1982 El Chichon eruption, the cooling effect of stratospheric aerosols must be compared to the warming by trace gases which have not yet achieved their equilibrium effect; it is not obvious that a global cooling of several tenths of a degree (Robock, 1983) should actually be expected. These problems should be studied by using a global model in which the atmospheric composition changes with time in accord with measurements, and in which the atmosphere, land and ocean each have realistic response times.

Summary

Climate Sensitivity Inferred from 3-D Models

Our analysis of climate feedbacks in 3-D models points strongly toward a net climate feedback factor of $f \sim 2$-4 for processes operative on 10-100 year time scales. The water vapor and sea ice feedbacks, which are believed to be reasonably well understood, together produce a feedback $f \sim 2$. The clouds in our model produce a feedback factor ~1.3, increasing the net feedback to $f = 3$-4 as a result of the nonlinear way in which feedbacks combine.

Present information on cloud processes is inadequate to permit confirmation of the cloud feedback. However, some aspects of the cloud changes in the model which contribute to the positive feedback appear to be realistic, e.g., the increase in tropical cirrus cloud cover and the increase of mean cloud altitude in conjunction with more penetrating moist convection in a warmer climate. It seems likely that clouds provide at least a small positive feedback. More realistic cloud modeling, as verified by detailed global cloud observations, is crucial for improving estimates of climate sensitivity based on climate models.

Climate Sensitivity Inferred from Paleoclimate Data

Analysis of the processes contributing to the cooling of the last ice age shows that feedbacks provide most of the cooling. The paleoclimate studies serve as proof of the importance of feedback processes and permit quantitative evaluation of the magnitude of certain feedbacks. The CLIMAP data allow us to evaluate individually the magnitudes of the land ice ($f \sim 1.2$-1.3) and sea ice ($f \sim 1.2$) feedbacks for the climate change from 18K to today, and to establish that the vegetation feedback was smaller but significant ($f \sim$

1.05-1.1).

We obtain an empirical estimate of f = 2.5-5 for the fast feedback processes (water vapor, clouds, sea ice) at 18K by assuming that the major radiative feedback processes have been identified (as seems likely from consideration of the radiative factors which determine the planetary energy balance with space) and grouping the slow or specified changes of the ice sheets and CO_2 as the principal climate forcings. This estimate for the fast feedback factor is consistent with the feedback in our 3-D model experiments, providing support that the model sensitivity is of the correct order.

The strength of the feedback processes at 18K implies that only relatively small climate forcings or fluctuations are needed to cause glacial to interglacial climate change. We do not try to identify the sequence of mechanisms of the glacial to interglacial changes, but it seems likely that both the direct effect of solar radiation (Milankovitch) changes on the planetary energy balance and induced changes of atmospheric composition, especially CO_2, are involved.

Climate Sensitivity Inferred from Recent Temperature Trends

The temperature increase believed to have occurred in the past 130 years (~0.5°C) implies a climate sensitivity 2.5-5°C for doubled CO_2 (f = 2-4), if (1) added greenhouse gases are responsible for the temperature increase, (2) the 1850 CO_2 abundance was 270±10 ppm, and (3) the heat perturbation is mixed like a passive tracer in the ocean. This technique inherently yields a broad range for the inferred climate sensitivity, because the response time for the ocean increases with increasing climate sensitivity.

Thus the 3-D climate model, the 18K study and the empirical evidence from recent temperature trends yield generally consistent estimates of climate sensitivity. Our best estimate of the equilibrium climate sensitivity for processes occurring on the 10-100 year time scale is a global mean warming of 2.5-5°C for doubled CO_2.

Transient Climate Response

The rate at which the ocean surface can take up or release heat is limited by the fact that feedbacks come into play in conjunction with climate change, not in conjunction with climate forcing. Thus the (isolated) ocean mixed layer thermal relaxation time, commonly taken as 3-5 years, must be multiplied by the feedback factor f. This, in turn, allows the thermal inertia of deeper parts of the ocean to be effective. If the equilibrium climate sensitivity is ~4°C for doubled CO_2 and if small heat perturbations behave like observed passive tracers, the response time of surface temperature to a change of climate forcing is of order 100 years. If the equilibrium sensitivity is 2.5°C, this response time is about 40 years.

We conclude, based on the long surface temperature response time, that there is a large growing gap between current climate and the equilibrium climate for current atmospheric composition. Our projections indicate that within a few decades the equilibrium global temperature will reach a level well above that which has been experienced by modern man.

Is there a point at which the perturbation of surface climate will be large enough to substantially affect the rate of exchange of heat between the mixed layer and deeper ocean, possibly causing a rapid trend toward the equilibrium climate? This question is similar to one asked by Representative Gore (1982): "Is there a point where we trigger the dynamics of this (greenhouse) process, and if so, when do we reach that stage?". With present understanding of the climate system, particularly physical oceanography, we can not answer these questions.

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Appendix A: Influence of Feedbacks on Transient Reponse

Consider a planet for which the absorbed fraction of incident solar radiation (1 minus albedo) is a linear function of the temperature, say x + yT. If the planet emits as a blackbody its temperature is determined by the condition of radiative equilibrium

$$s_0 a_0 = \sigma T_0^4 \qquad \text{(A1)}$$

with s_0 the mean solar irradiance and $a_0 = x + yT_0$.

Now suppose the solar irradiance changes suddenly by a small amount Δs. At the new equilibrium

$$(s_0 + \Delta s)(a_0 + \Delta a_{eq}) = \sigma(T_0 + \Delta T_{eq})^4 \quad . \qquad \text{(A2)}$$

Neglecting second order terms (since $\Delta s << s_0$) and using (A1) yields

$$\Delta s a_0 + s_0 \Delta a_{eq} = 4\sigma T_0^3 \Delta T_{eq} \quad . \qquad \text{(A3)}$$

If there were no feedbacks ($\Delta a_{eq} = 0$), the temperature change at equilibrium would be

$$\Delta T_{eq}(\text{no feedbacks}) \equiv \Delta T_0 = \frac{\Delta s a_0}{4\sigma T_0^3} \quad . \qquad \text{(A4)}$$

Thus we can rewrite (A3) as

$$\Delta T_{eq} = \Delta T_0 + g \Delta T_{eq} \qquad \text{(A5)}$$

where

$$g = \frac{s_0 \Delta a_{eq}}{4\sigma T_0^3 \Delta T_{eq}} = \frac{s_0 y}{4\sigma T_0^3} \qquad \text{(A6)}$$

Using the relation between gain g and feedback factor f, $f=1/(1-g)$, equation (A5) becomes

$$\Delta T_{eq} = f \Delta T_0 \qquad \text{(A7)}$$

i.e., the equilibrium temperature change exceeds the no-feedback equilibrium temperature change by the factor f.

The heat flux into the planet as a function of time is

$$\begin{aligned} F &= \Delta s a_0 + s_0 \Delta a - 4\sigma T_0^3 \Delta T \\ &= 4\sigma T_0^3 (\Delta T_0 + g\Delta T - \Delta T) \\ &= \frac{4\sigma T_0^3 \Delta T_0}{\Delta T_{eq}} (\Delta T_{eq} - \Delta T) \\ &= \frac{F_0}{\Delta T_{eq}} (\Delta T_{eq} - \Delta T) \end{aligned} \qquad \text{(A8)}$$

where

$$F_0 = 4\sigma T_0^3 \Delta T_0 = \Delta s a_0 \qquad \text{(A9)}$$

is the flux into the planet at $t = 0$ (i.e., when $\Delta T = 0$). Thus the initial rate of warming is independent of the feedbacks.

The temperature of the planet as a function of time is determined by the equation

$$\frac{dc\Delta T}{dt} = c\frac{d\Delta T}{dt} = F \qquad \text{(A10)}$$

where c is the heat capacity per unit area. If c is constant (e.g. a mixed layer without diffusion into deeper layers), the solution is

$$\Delta T = \Delta T_{eq}(1 - \exp(-t/\tau)), \qquad \text{(A11)}$$

$$\tau = f \frac{c}{4\sigma T_0^3} = f\tau_b \qquad \text{(A12)}$$

where τ_b is the no-feedback e-folding time [Equation (22)].

Finally, note that these results are much more general than the specific mechanism we chose for the feedback, which was only used as a concrete example. It is apparent from the above that the only assumption required is the linearization of the feedback as a function of temperature.

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Mr. GORE. Well, thank you. Thank you very much.

Well, we've got an interesting range of opinions here. The EPA says it's too late to act. The NAS says it's too early to act, and the Friends of the Earth say it's time to act. [Laughter.]

Our natural inclination in political systems is to side with those who say it's too early to act. That's just the political inertia that's a fact of life around here, and I assume in other countries as well. But let me try to draw you out, Dr. Malone, on why you all say it's too early to really be overly concerned about this.

Mr. MALONE. Mr. Chairman, one of the compensations of growing old is that you live through experiences. I have lived through the ozone depletion experience, and I recall a few years ago strident voices being raised that we should do something; there was a pending catastrophe. If we didn't, the human race would suffer.

The Academy has been preparing reports on this over the past decade, and the best estimates of the depletion of ozone by all these has dropped from about 18 to 9, and I think within the past week it's down to around four, and this came as the result of increased knowledge—not stupidity back there, but increased knowledge. This is the plea we're making, is to build that knowledge in so that when we do act, we will be acting on a firm intellectual and scientific basis.

Mr. GORE. Well, looking at the ozone precedent, I know there was a recent revision in the last week or so, but wasn't that essentially on target? I mean, the concern was essentially justified, wasn't it, and action was taken. Congress acted, I know. There was a change in the usage pattern, and I thought that that concern was essentially justified, wasn't it?

Mr. MALONE. I don't think it was. I don't think the action taken is what has reduced the———

Mr. GORE. Oh, well, I didn't mean to imply that, although I think that's open to argument as to what effect it had. It's probably quite small but, coming back to the central point, the concern that was expressed over the ozone and halocarbons was essentially correct, wasn't it?

Mr. MALONE The models at that time overestimated the impact of the various things that go into the stratosphere, and as the knowledge has grown and the models have improved, the estimates of this impact have steadily declined so that it is much less a formidable problem today than it was 10 years ago.

Mr. GORE. But still formidable, correct?

Mr. MALONE. Well, I think that's beginning to be open to question.

Mr. GORE. Really?

Mr. MALONE. If you're talking about a 2- to 4-percent decrease and you look at the normal noise level in the ozone content, you're getting down to where you can hardly measure that. I don't mean to belittle the ozone problem.

Mr. GORE. I thought that's precisely what you intended.

Mr. MALONE. No. I'm simply saying that it is an illustration of where, if all the recommendations had been followed when the issue was first raised, we would have been acting on incomplete information which has only recently become available. My case is not on the ozone but on the desirability of having adequate information on which to base action.

Mr. GORE. The old saying is that the better is the enemy of the good, and the best is the enemy of the better. If, in fact, we are in a time where action must be taken soon in order to prevent worse damage than is already locked in, then a decision to hold off any sort of action or planning for action, pending much better information, is not a value-neutral decision. It is one that has consequences, just as a decision to act would have consequences.

What I really want to get at, and we can leave open the discussion of the ozone thing—I agree with you that it's not the central point here, but you brought it up. I wanted to make the point that essentially the judgment made there was correct, even though the estimates were high in the beginning. But on the greenhouse effect, you all seem to take a very benign view of the impact of this phenomenon, and I don't quite understand fully why. You say that the temperature will probably go up between 2 and 8 degrees. Is it that that doesn't sound like much?

We heard earlier testimony from the panel just before this one that looked at the ice ages, for example, and demonstrated that the ice ages were caused by a temperature differential in the same order of magnitude—a few degrees—as what we're talking about here. We heard testimony about it not being a linear problem where the changes are just gradual and it just seems like a couple of degrees warmer each day on average, but rather the problem is one where the equilibrium point of the world climatic system changes probably—may change—in radical ways to produce a totally new equilibrium point with totally new patterns in rainfall, drought, climatic patterns affecting a whole range of human activities.

Why is it that you look at a temperature rise of 2 to 8 degrees and take a rather relaxed viewpoint, a rather relaxed attitude toward it, when others look at the very same temperature rise and see a pretty dramatic set of consequences flowing from that?

Mr. MALONE. Well, Mr. Chairman, if I have conveyed the impression that we do not take seriously a 2 to 8 degrees Fahrenheit change in world temperature—and you will recall that that means about three times that in the polar regions, which would affect the storm tracks—I have not communicated our concern properly to you. This would have a serious effect. It would affect our Midwest. It would affect the coastlines. Our point simply is that there are sufficient uncertainties about this, and the way is open to minimize those uncertainties, and that is the desirable course of action for the immediate future.

We published back in 1977, under a committee I chaired, a report that I think you're familiar with that Roger Revelle really put together on energy and climate. We were one of the fairly early ones to identify this problem, and our emphasis has been continually on acquiring the kind of information upon which intelligent action can be taken to forestall or to adapt, and there is a basic philosophical difference here between those who say, "What we have now is what we want. Anything to change that is automatically bad."

Now on agricultural productivity, if you look at the gains in agricultural productivity over the past 20 years, which have been fantastic, they show all the promise of being able to adapt to the kind of changes which would take place regionally under the scenarios that are being developed. It is the capacity of our system to adapt to these new conditions at a rate which compensates for the changes that is the important issue.

Mr. GORE. OK. Now let me try to sort that out. First of all, I don't disagree, and I doubt that anyone who has looked at this issue carefully would disagree with your call for better information—more research, a refinement in our understanding of the problem. I am in total agreement with you there. Yes, we need to do that.

Now, second, there is indeed a philosophical issue here and the choice between adaptation and a decision to try to forestall these changes, if it turns out to be possible to do so. That choice is affected more than anything else by the attitude of the scientific community toward the consequences of this thing taking place. If the scientific community says, "It may not be so bad; genetic engineering of plants may make it possible to grow things in the desert"—and I am exaggerating there, but it may not be so bad—then that speaks to that philosophical issue.

It seems to me that the tone of the NAS report comes down on the side of adaptation. Figure out how to most efficiently evacuate 60 percent of Florida, 40 percent of Florida. Figure out how to adapt genetic strains of plants. Do some long-range planning for evacuating New Orleans and Bangladesh and San Francisco. I mean, you can tick off the list. The point I am getting at is, your tone and your attitude is something that I don't understand, and I want you to help me understand it because it seems like an overly benign view of how catastrophic these changes could be which could occur. Do you understand the point I'm getting at?

Mr. MALONE. Yes, sir. When we first surfaced this in 1977, I made the comment that the report at that time was a flashing yellow light, not a red light. It just came out at the time that a large energy program was being considered.

I think the point on which we can converge is the distinction between action and planning for action. The first conclusion that I read to you was priority attention to long-term options that are not based on combusion of fossil fuels. We believe this is a serious problem. That's why we spent that much time bringing the best minds we could get to bear on this, and a review process which the Academy has never seen the likes of. The result of this is that we do not feel that abrupt action is required at this time, when we have not yet been able to identify clearly a climatic change associated with increased carbon dioxide.

Mr. GORE. Now say that again. Say that last point.

Mr. MALONE. We have not yet been able to identify changes in the climate that are unmistakably related to increased carbon dioxide. In other words, the normal fluctuations in the climate are sufficiently large that if there are CO_2-induced changes they are buried in the noise, and one of the purposes of monitoring is to detect that as early as possible so that at that time we can press the start button.

Mr. GORE. Well, we had testimony at an earlier hearing from the NAS folks which did correlate the CO_2 increases or appeared to correlate them with a melting or a shrinking of the ice cap in Antarctica and a rise in the sea level over the past 50 years. I know you're familiar with that. Am I misinterpreting the import of that work?

Mr. MALONE. No. You are simply identifying the diversity which exists within the scientific community. No one, least of all the National Academy, speaks infallibly. There are those who—competent, responsible scientists—who feel that they have detected the first signal of a CO_2-induced climate change. By and large, the consensus in the scientific community—and the individuals may be right and rest may be wrong—but the consensus is that we have not yet been able to detect that first signal.

Mr. GORE. Do you agree with that, Mr. Hoffman?

Mr. HOFFMAN. Yes, I think that that is accurate. I think that Dr. Hansen's work was showing that the temperature rise that we have seen is consistent with the theory that the greenhouse effect is taking place. The problem is that you haven't had enough temperature change for you to be statistically sure that that is the case, and you have to understand what people mean when they say "statistically sure." Scientists don't operate on the basis of it's 3 to 1; they don't operate on the basis that it's 9 to 1. Most scientists operate on the basis that it's 19 to 1 that this couldn't happen by chance, and that kind of test hasn't been met yet.

Mr. MALONE. Mr. Chairman, I don't want to convey on my own part or on the part of the Academy a sense of complacency on this problem. We think that it calls for a vigorous and expanded program of research. It was precisely, to a large extent because of this problem that we mounted the climate research program, a thoroughly international enterprise.

It is in large part because of the need to monitor not only the atmosphere but the biosphere and the oceans that we are moving aggressively toward an international geosphere/biosphere program. This is our response to an unparalleled geophysical program that society is carrying out, with results which we are—with an outcome which we are not yet able to perceive in a satisfactory manner, but the prospects of being able to do this with added and augmented information is something we are completely dedicated to.

I think the distinction is pressing for action or pressing for the knowledge upon which to base action, and we are far from complacent on pressing for this knowledge on which to base action. We are reticent to urge action until that knowledge base is in place. Does that ring true with you?

Mr. GORE. Well, it's a tough one. It's a tough one. Everybody agrees with that. I guess I'm worried that the philosophical choice will be made by default, and that the only way we are going to avoid choice by default is by having a fully adequate appreciation of how severe these consequences are.

Dr. Kukla testified before our hearing that since the 1930's a band of ice 180 miles wide in Antarctica has melted already. That's a lot. That's not speculation. I mean, that's not a theory. I mean, if you accept his methodology, that's something pretty dramatic.

Mr. MALONE. Mr. Chairman, does he maintain that that was a result of increased carbon dioxide? I doubt very much whether Professor Kukla would make that kind of a comment.

Mr. GORE. Well, the record will speak for itself and you and I can both review it for the record of this hearing, but——

Mr. MALONE. I would be glad to provide you——

Mr. GORE. He said in his testimony that the measurements and the melting correlated precisely with what the models, the CO_2 models predicted he would find. Now, you know, that's something.

But let's move from what has happened in the past to what you agree on. You agree, you agree that it's quite likely we'll see a temperature increase of 2 to 8 degrees in a relatively short period of time and, you know, we can argue about whether it's children or grandchildren. Tell me why you don't think that a temperature increase of 2 to 8 degrees is not going to produce extremely disruptive, dislocating consequences for our country, for the United States? Let's put it in those terms.

Mr. MALONE. Mr. Chairman, I have not made myself clear. I do believe that a 2 to 8 degree temperature change would have dramatic effects on our country. I simply am saying that there are enough uncertainties surrounding this whole problem, that to take action today is premature. We are in complete agreement about the potential impact of the kind of temperature rise and climatic change that would take place. The question is, when do we push the start button?

Mr. GORE. Yes, but there's a difference between saying—and I'm going to get to you, I know you're itching to say something, Mr. Pomerance—but there's a difference between saying yes, these changes are catastrophic if they are going to occur, but we don't have enough information yet to say with certainty they will. That is one statement.

On the other hand you can say things which I thought I heard you saying, like, We can adapt to this. Our agriculture has produced dramatic breakthroughs over the last 20, 30, 40 years, and there is no end to what we could do to adapt to this, and it may not be all for the bad. There may be some good things coming out of it.

You yourself said, to assume that the equilibrium point that we now have is the best may be chauvinsitic in some way, and that maybe there is some better equilibrium point.

You see, that's different from saying the uncertainties ought to keep us from acting. That is speaking to the philosophical issue and implying—unless I'm hearing you wrong—implying that maybe the best choice, even if the uncertainties are resolved, maybe the best choice would be to just let it happen and hope for the best.

Mr. MALONE. Mr. Chairman, you could help me if you could share with me what you think that action should be. What action do you think we should take today? Maybe I agree with you completely. What do you think we should do now?

Mr. GORE. Well, you know, that's the overall effort of these hearings, but it would clearly speak to the volume of fossil fuel use. It would speak to the benign attitude toward deforestation in the world, and it would speak to conservation, efficiency, and global energy policies. Now the range of our disagreement may not be much, but the perception of the problem that we together develop—and when I say "we" I mean the scientific community and the political community—may be of the utmost importance.

It really may be of tremendous importance because, if the assumptions are correct, then there will be no greater environmental challenge facing our global civilization save nuclear winter and it may overwhelm our ability to respond. If we have any hope of responding in a wise fashion, then the communication between our two communities has got to be better than it has been at any point in the past.

You wanted to speak, Mr. Pomerance, and then I will come back to you, Dr. Malone.

Mr. POMERANCE. A couple of thoughts: One is, I don't—I think that one of the problems with the "wait and see" attitude, and the EPA gets that, that is to say "wait and see," the assumption of "wait and see" is that you can then avoid 2 to 8 degrees, and I think the EPA challenges that for the first time in a major way. The CEQ did it in 1980, I believe. They challenged the assumption, if you wait until the year 1995 before the scientific community speaks with a consensus, what do you have to do then to avoid 2 degrees centigrade? I don't believe that they know the answer to that. The NAS I don't think has answered that question.

The longer we wait, the more CO_2 we are locked into, because we are sitting on a very powerful engine, world coal use. If you say, "Stop," it's going to take a long, long, long time to stop. It's as though, you know, you were going over a rickety bridge in a locomotive. Well, as soon as you think you can stop when the red light goes up as you are about to go over the canyon, it flashes stop but you've got too much momentum, so you're over the canyon on the rickety bridge. It's too late.

I don't think that, so long as I have watched this issue, that the people haven't figured out when they have to begin acting in order to avoid a consequence four or five decades later. It appears from what EPA said that in fact we're past a good portion—in other words, we've already used up a part of that time and we have banked temperature increases that we haven't seen, if Dr. Hansen is correct, so we're all behind. In fact, we have made a decision to let things warm up. What we haven't done is make a decision to try and minimize the warming or let it go on.

Mr. GORE. Dr. Malone, you all disagreed with the EPA's conclusion that it was really too late to have any effect, or did you?

Mr. MALONE. Was that the conclusion that you——

Mr. HOFFMAN. Well, I don't think really that, if you look at the work that Bill Nordhause did, that he really disagrees with us at all. Essentially both reports show that if you take action, it's going to take a long time for the action to work, and that it's only going to have a relatively small effect on the amount of carbon dioxide that's put in the atmosphere. He actually tests some tax policies in his chapter that show that.

I would like to just correct one thing about the statement you made about our reports, which is, we don't make any policy recommendations in the report. It's just purely analysis. We look at what happens if somebody decided, if the world decided to have a certain policy at a certain date.

Mr. GORE. Yes.

Mr. HOFFMAN. We don't say whether it's good or it's bad. We are just saying these are sort of what the future would look at if people made these choices.

Mr. GORE. Yes, but you assume that—you say that some hypothetical policies that sound very, very extreme—a total ban on coal usage——

Mr. HOFFMAN. Right.

Mr. GORE [continuing]. You analyze that and say, "It doesn't really matter. You could totally ban all coal burning and it would only delay the 3.6-degree Fahrenheit rise from the year 2040 to the year 2055."

Mr. HOFFMAN. That's right. What we found in the study was that it won't matter very much in terms of the next 60 years. If you look at it and you extend the curve out, by the year 2100 it has a very substantial effect, but by the year 2040 it only—the coal ban only delays 2 degree warming something like 15 years, if it's fully effective by the year 2000.

Mr. GORE. Well, let me see if I can pinpoint the difference between EPA and NAS on this. I don't think I'm wrong in saying that there is one, but you all can correct me if I am. The NAS was more cautious in its predictions about non-CO_2 trace gases. Is that a fair statement?

Mr. HOFFMAN. Well, you see, the NAS didn't make a year-by-year prediction of how the temperature was going to rise. The NAS report looked at the trace gases and it looked at the CO_2, but it never combined those to simulate how the climate would change as the oceans are taking up heat, and I think that's the thing that our report did differently. Their report was focused on a much broader range of issues—on the agricultural impacts, on lots of other things, on whether you needed to look at water resources.

The "can we delay" study just looked at this one narrow focus: What's the time trend of climatic change and what could we do about it if we implemented various fossil fuel policies. The reports aren't very different. In terms of carbon dixide, in the year 2050, for example, the "can we delay" report actually has 15 parts per million less carbon dioxide in the air than Bill Nordhaus' mid-range estimate.

Mr. GORE. Well, the impression I got overall of your report was that you were saying there is no reasonable step which civilization can take which would significantly delay the greenhouse effect.

Mr. HOFFMAN. Well, I think that in terms of what's going to happen in the next 60 years, I think that that's accurate.

Mr. GORE. Do you agree with that, Dr. Malone?

Mr. MALONE. It takes about 70 years to introduce a new technology into society. This is the conclusion that came out of the Haefule study in Laxenburg. Renewable resources account for about 20 percent of the world energy supply. To raise that up to something like 80 percent, 90 percent, would require something on the order of 70 years, yes.

Mr. GORE. So you would agree with the statement that there is no reasonable action available to civilization which would significantly delay the greenhouse effect?

Mr. MALONE. No. If we—there is no single action. There is a set of actions: emphasis on renewable resources; emphasis on solar energy; more attention to the vexing problem of nuclear energy. It's an array of actions rather than one silver bullet that is likely to ameliorate this problem.

Mr. GORE. But if a set, if that array of policies was somehow implemented, then it would or could significantly delay the greenhouse effect?

Mr. MALONE. Yes, sir.

Mr. GORE. So there is some difference in emphasis there.

We're running way overtime, and I am going to have to apologize. Did you want to say something, Mr. Perry?

Mr. PERRY. Well, I simply wanted to point out that if you look at the different runs in Nordhaus' paper, the different scenarios, you find that some possible paths through the future have rather low—yield rather low carbon dioxide concentrations, and these are paths associated with the availability of cheaper nonfossil sources, lower productivity growths in the economy, et cetera. I think the fact that within the confines of his model Nordhaus was able to generate some low-CO_2 scenarios that shows it's possible for the world economy to evolve in a fashion that would produce less CO_2, so we shouldn't despair.

Mr. GORE. Mr. Pomerance, did you want to comment on the issue that I was discussing here, about——

Mr. POMERANCE. Yes. I don't think it was adequately addressed. The EPA says we're locked in, basically, to some early portions of a greenhouse effect. If you are going to avoid any more catastrophic greenhouse effect, you have to move. Every year that you wait makes it that much more difficult to do.

It so happens that the most easily available strategy to begin to deal with it has other benefits as well. I mean, it's not—energy efficiency, which is the major strategy available, is one that there is a fairly wide consensus on in the industrial community, the business community, and so on. This issue is so big, yet the attitude that is being taken is so relaxed. I mean, it strikes one as a bit incredible. If the mid-range in the NAS in the year 2050 is not far different from EPA, it is a frightening prospect, and I think we do have one strategy that is available to us which is a massive commitment of capital to energy efficiency. We also can do something about some of the trace gases which, in fact, the NAS—although saying we have more time—does say that we ought to begin there, with the chlorofluocarbons, perhaps

I guess maybe the major missing element in all this is leadership. If you saw what the President's science advisor had to say about this, you might have been quite discouraged after he dismissed it as an important issue. We need leadership, and I happen not to think it needs to come from the scientific community. I think it needs to come from the political community.

Mr. MALONE. Mr. Chairman, I do hope that you will continue this exchange which has gone today and has gone on in the past. I am persuaded that reasonable people will converge on a course of action, and I am just delighted that you have called us. If I have inadvertently conveyed a sense of complacency on the part of the scientific community, that was not my intent. I am deeply disturbed by the prospects.

I think it is a question of how we proceed over the next few years. Do we develop and mount a crash program or do we do some of the things that have been described here this morning to make our knowledge base a little more secure? But I do hope that you will keep this dialog going because it is absolutely essential that the political decisionmakers and the scientific community, if there is such a thing, communicate freely and openly.

Mr. GORE. Good. Well, I appreciate that statement very much, and I will continue to pursue this issue vigorously. It is a hard one. It is really hard, and in a comparable dialog between policymakers and their political constituencies this knowledge base is absolutely essential. I mean, you talk about such tremendous effects and such dislocating responses, if they were implemented, you have to have a degree of certainty that is fairly high in order to justify this.

But in light of the, you know, what I think are unacceptable consequences, there is a trade-off between the degree of certainty and the time for action. Where that point is, we may have already passed it.

We may have already passed it, but a continued dialog is essential and I appreciate the work that all of you have done and your participation in this issue. I wish we had more time to continue it, but we don't. Thank you very, very much. I appreciate it.

Now we are going to have to have a very abbreviated treatment of our final panel, and I hope they will forgive me for this, but the room is spoken for right after the end of this hearing. So if Mr. James S. Kane, Deputy Director of Energy Research at DOE, will come to the witness table, accompanied by Frederick Koomanoff, Director of the CO_2 Research Division in the Office of Basic Energy Sciences, I am going to apologize to both of you for the fact that we're not going to spend much time here.

Mr. Kane, you have a prepared statement, do you?

Dr. KANE. Yes, I do.

Mr. GORE. Without objection, we are going to include that in the record, and we will have a number of questions in writing. Can you respond to those questions in writing?

Dr. KANE. We certainly will, to the best of our ability.

Mr. GORE. In the short amount of time that we have, can you summarize the most important thing that you think needs to be said at this point in the hearing?

Dr. KANE. Do I have what, 10 minutes?

Mr. GORE. Five minutes.

Dr. KANE. Five minutes? All right, I'll try.

STATEMENT OF DR. JAMES S. KANE, DEPUTY DIRECTOR, ENERGY RESEARCH, U.S. DEPARTMENT OF ENERGY, ACCOMPANIED BY FREDERICK A. KOOMANOFF, DIRECTOR, CARBON DIOXIDE RESEARCH DIVISION, OFFICE OF BASIC ENER... SCIENCES

Dr. KANE. I have been busily adapting my testimony anyway as we were going along, because so much has been said already and to repeat it would be a waste of everyone's time.

I think I would like to synthesize one thought that I heard from every witness that was here, and that was this element of uncertainty. Every person here that made a prediction, when you pressed him as you did, even our expert scientists changed their words "will" to "may," very obviously, so uncertainty is really the point of the whole DOE program, to reduce this uncertainty.

It's good for two reasons: We can't make sensible predictions unless we do and, second, you could not mobilize the constituency on the basis of uncertainties. You really have to have more to go to the constituency with, to address them, in case a response is called for. I will avoid that problem, because I thought you and Mr. Malone and Mr. Pomerance explored that very well.

Let me then just briefly—and I'm talking fast, I hope not too fast—go through our progress last year. We think this program—and Mr. Koomanoff is here with me, and we brought a picture but I'll just defer talking about that. You might want to look at it after the hearing. I was going to mention the report of the National Academy of Sciences. I don't believe I'll do that, since you had an opportunity to explore it, other than that we do side with their viewpoint to a large extent.

We have some interesting results on the response of vegetation to the increases in CO_2. While it has been suspected for many years that plants would grow more rapidly in increased CO_2, since that's their food, for the first time we actually did experiments in cooperation with the U.S. Department of Agriculture on field tests of soybeans and corn, and sure enough, two things came out of it: One, both soybeans and corn respond by growing faster, and appreciably faster, as the CO_2 level is increased. Second, the plants' ability to use water, a very critical aspect everywhere but the arid West particularly, increases as the concentration of CO_2 increases.

Now we are not advocating increasing CO_2 to make our plants grow faster, but we need this information to balance the scientific books. We can't understand what the previous witness talked about—where does the carbon come from and where does it go to?—unless we understand the uptake of CO_2 by plants.

Finally there is this subject you alluded to briefly, and it's good news and nothing we had anything to do with, and that is the decreased use in energy per GNP of the Western World, at least. For a long time, it's very clear, since about 1974, that we are using less energy in the Western World. It wasn't clear whether this was a result of the worldwide recession or whether it was a result of efficiencies, but if you look at it in the aspect of the amount of energy it takes to produce a unit of GNP it, to at least some extent, disentangles the recession aspect. It's very clear that the Western World at least has a greatly reduced rate of carbon consumption per unit of GNP. This has the effect of delaying the onset of whatever is going to happen by some period of time. We're clearly using less.

Now the undeveloped world is kind of divided into two parts, those who would like to use energy as profligately as we do but can't afford it, and ones like the Chinese who have the energy and may well use it, and they are growing at a much faster rate than the developed world.

I think that's about enough, other than the international outreach. We've made a log of the people working on this problem throughout the world. There's over 1,600 and 40 percent are outside the United States, which gives me pleasure, extending as far as China, the People's Republic—which have, by the way, 500-year-old weather records, which is unique in the world.

I will skip now, then—that's kind of a résumé of what happened last year—to what we're going to do in the coming year. Certainly you have heard from all concerned that we have to improve our models. There is just absolutely no doubt about that. You heard Professor Sagan say we'll never get them to the point where we'll be able to say, "This will happen in the world at a certain time." Very true. Models really use two things to predict. They use an input of science—physics, chemistry, meteorology—and they also use estimates of what future consumption will be. Both of those are extremely difficult.

We're going to work on our models from really two points. One is to get greater spatial resolution. It really doesn't help much if I tell you that the average temperature of the world is going to change. What you really need to know to take action is localization and waterfall, along with the change in temperature. You need to know what's going to happen to a certain area, how the temperature and the rainfall will change. Our current models are totally inadequate to make those kind of predictions.

A 1-degree average in the world doesn't mean much. I keep kidding Fred that he should release more CO_2, this has been a terribly cold winter this year, and he tells me that's not true, that worldwide this is not a very cold winter, so you see the importance of regional predictions rather than just the worldwide average.

Another thing we're going to do is to launch—by the way, the two witnesses that covered the importance of the ocean, we couldn't agree more. I don't think it has been negligence or stupidity on our part. Modelists tend to do first things first. They treat what they can first. What they can't handle, they treat with simple approximations, and I think the two witnesses—Dr. Broecker and Dr. Jenkins—make a pretty convincing case we can't treat the oceans as simple approximations much longer. We're going to have to get much smarter about what's happening out in the ocean or our models will be pretty meaningless. We intend to do that in the coming year.

We also have asked for—although this is not a budget hearing—an additional $900,000 next year to look at the trace gases, a worrisome question that really needs more examination. You might be interested to know that some of the predictions on sea level rise really result more from increase in those trace gases, if you look at the innards of the model, than they do from CO_2 increase, so we can't afford to talk about CO_2 as though it were the single problem that we're faced with, so we're asking for that.

Next year, to hurry along, there are going to be a number of forthcoming reports. We will have state-of-the-art reports which pick single topics, and we'll write them up. We'll have them peer-reviewed by the AAAS to give scientific uniformity and quality to them, and publish them. We will also try to wrap these state-of-the-art reports up into a single statement of findings, which will be the state of the art—what we know, what we don't know, what the uncertainties are, and what we think should be done.

That's a race through in 5 minutes.

[The prepared statement of Dr. Kane follows:]

Statement of Dr. James S. Kane

Deputy Director Office of Energy Research

Department of Energy

Mr. Chairman and Members of the Subcommittee:

It is a pleasure to appear before you today to describe the Department's Carbon Dioxide research activities. The Department's FY 1985 budget request for this activity is $13.5 million.

The "greenhouse effect" has become a household word. National television, news weeklies, local radio stations through national wire services, and even comic strips have carried the news of the potential warming of the earth due to an increase in CO_2. The public is told that the increased CO_2 levels are due largely to our use of fossil fuels. That the public is becoming increasingly aware of the issue is a natural consequence of the active CO_2 research for which the DOE has had the lead responsibility over the past 7 years and the publicity surrounding it.

The Department of Energy was originally asked to initiate a specific research program directed toward understanding the effects of increasing atmospheric carbon dioxide. Shortly thereafter the National Climate Program Office designated the DOE as the lead agency for coordinating the Government's research efforts on this issue. The functions assumed by the DOE Carbon Dioxide Research Program in this role were to:

- Coordinate federal research related to CO_2;
- Sponsor specific projects that would increase the knowledge base and support refinement of the conceptual tools being used to help understand the phenomena;

- Perform continuing technical reviews of the worldwide research effects; and

- Communicate to all interested parties, domestic and international, the scope, progress, and findings of the research.

It is evident from our findings and those of others that the CO_2 question remains an important research issue. The research problem is complex and many talents and scientific disciplines will be required to resolve it. In spite of the effort to date, scientific uncertainties remain. Under the current research program, the Government and scientific community, however, have defined the approaches for reducing these uncertainties.

Several reports dealing with the CO_2 issue have been published recently. The Department of Energy was pleased that the National Academy of Sciences' report, Changing Climate, focused on scientific uncertainties. We agree with the Academy position that increased scientific understanding of CO_2 is needed. Their conclusion is reasonable: we have time to conduct the needed research.

Today I will cover recent progress and discuss some unresolved issues. In addition, I will describe the reports we plan to publish early next year.

Progress

Publications. As part of its mission to coordinate the research, the Department of Energy has published a series of carbon dioxide research plans. These plans provide all participants and other interested parties with a clear picture of the current scope and activities of the Carbon Dioxide Research Program and the directions for the near future. Copies of the draft plans were sent to this committee in early 1983.

The summary plan published in December 1933 delineates the logic, objectives, organization and background of the research activities. The Carbon Cycle and CO_2 Climate Research Plans and the Reponse of Vegetation to Carbon Dioxide Research Plan, released in December 1983 and January 1984, emanated from a series of national and international workshops, conferences, and from technical reports. All the plans were reviewed by experts in the relevant scientific fields. Implementation of the plans is being coordinated among the responsible Federal and international institutions and the involved scientific community.

In addition, we have initiated a carbon dioxide technical report series to supplement material appearing in proceedings, scientific journals, and other literature. To date seven technical reports have appeared and we expect to publish approximately 30 more by the end of 1984.

International Initiatives. Our report, International Carbon Dioxide-Related Activities: The International Organizations Involved and U.S. Bilateral Arrangements documents the groups that are involved internationally in CO_2 research. A directory of approximately 1600 scientists in the international science community has been developed; 40% are outside the United States. Discussions are underway with the Peoples Republic of China concerning possible joint activities, such as using their 500 years of historical climate data in our modeling efforts. In addition, discussions have been held with representatives of the international effort on CO_2 assessment at the World Meteorological Organization - United Nations Environmental Program. These activities continue to enhance our international outreach.

Nineteenth Century Atmospheric CO_2. It is critical to know the atmospheric CO_2 level before substantial amounts of CO_2 were added from fossil fuels and land clearing. This "preindustrial value" is an important initial condition for modeling past, present, and future climate change.

A new estimate of 19th century CO_2 was made at a recent World Meteorological Organization (WMO) meeting of experts. The new estimate is in the range of 260 to 280 parts per million (ppm). Data from four laboratories supported by the DOE program contributed significantly to the new consensus. These laboratories are the Carbon Isotope Laboratory at the University of

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Washington, the Physical Science Institute at the University of Bern, Switzerland, the Woods Hole Oceanographic -stitute and the Pacific Northwest Laboratory. The WMO meeting of experts acknowledged that values on ice core measurements provided by the University of Bern are probably the most direct and accurate estimates of preindustrial atmospheric CO_2.

This new estimate has important implications for predicting the effects on climate. The previously accepted estimate for the preindustrial CO_2 level was 295 ppm. The new lower value affects climate model predictions of global average temperature. Using the previous estimates for CO_2-level changes, the global average temperature increase resulting from a doubling of atmospheric CO_2 would range from 1.5° to $4.5^{\circ}C$. Using the new estimate, the upper bound of the temperature increase is reduced substantially from 4.5° to $3^{\circ}C$.

Carbon Dioxide Standard Reference Gases. Accurate, high-quality atmospheric CO_2 measurements require standard reference gases. Instruments must be calibrated with these reference gases, and the use of a common calibration scale permits data from different laboratories to be easily compared. A program was developed with the National Bureau of Standards (NBS) and the Scripps Institution of Oceanography to produce these stable standards for atmospheric CO_2 measurements in the United States and other countries. As a result new CO_2-in-air Standard Reference Materials have been produced and distributed by the NBS. These standards were certified through cooperative research with Scripps, and the joint certification process assures contin ty with reference gases previously provided by Scripps. The NBS Office of S ndard Reference Materials will maintain and certify these standard sampl on a cost reimbursable basis.

Crop Response to Increased CO_2. Experience with plants grown in CO_2-controlled greenhouses or growth chambers suggests that more CO_2 increases plant productivity. In cooperative research involving the Department of Agriculture and the Department of Energy, soybeans and corn were exposed to increased levels of CO_2 for one entire growing season. For soybeans, an increase in productivity of at least 30% resulted from doubling of CO_2. For corn, a 10-20% increase was observed, with maximum productivity achieved at CO_2 levels of between 350 and 500 ppm. We are thus starting to get the quantitative information needed for an assessment of the direct effect of increased CO_2 concentrations on agriculture, under conditions similar to those of conventional cultivation practice.

One important effect of CO_2 on plants is to control ...ing c' the small pores in leaves which permit exhange of CO_2 and water vapor between internal leaf tissue and the atmosphere While the exact mechanism of the CO_2 effect on this process is not kn wn, it appears to result in improved plant water use. New data from outdoo experiments suggest that the water use efficiency may increase by 35% with a doubling of CO_2 levels. The most significant effect on corn is that while photosynthesis and yield are maintained or increased, water loss by the plant appears to be reduced. This could be an important development, because many plants regularly experience water stress, and additional CO_2 may partially alleviate the stress.

While these results are encouraging, much work remains. Additional research must be performed to validate these experiments. Work in different geographic locations with more crop varieties is necessary before we can conclude that field crops will generally benefit from elevated CO_2 levels.

Unresolved Issues

Climate Modeling. To predict the effects of increased atmospheric CO_2 concentration on climate, we must rely primarily on numerical models. Current climate models are not adequate to enable us to make policy decisions related to CO_2. Uncertainties concerning the role of clouds, sea ice variations, and atmosphere-ocean interactions prevent extracting regional detail (e.g., a projection for the U.S. corn belt) from the results. The large, three-dimensional models are called General Circulation Models (GCMs). The current range of model predictions is a 1.5^{o} to 4.5^{o} global average warming for a doubling of CO_2 (300 to 600 ppm). As mentioned before, more recent analyses of the climate data suggests that the CO_2-induced warming for a doubling is probably in the range of 1.5^{o} to $3^{o}C$.

To test the validity of the GCMs, several approaches are being pursued. The first approach is to evaluate separately each component of the model. Our approximations to radiative processes, such as the absorption of infrared radiation by CO_2, can be tested by comparing model results to laboratory and detailed atmospheric experiments. We are doing this in cooperation with the WMO.

A second approach to model validation is to compare climate model predictions with observations. When such comparisons are made, the predictions of the models agree well with the major features of the present climate on a global scale. Efforts to look at smaller areas (e.g., the U.S. corn belt) are limited because several important physical processes, as mentioned earlier, have not been well represented in the models.

A third approach is to evaluate the model response to various changing conditions. Even if the models can represent the present climate, it is not certain that they will be able to accurately project climatic changes; that is, although their average indications might be correct, that does not guarantee their accuracy when conditions change Testing the model representation of the seasonal cycle, which is a very large perturbation, evaluates those aspects of the model that respond very quickly (i.e., over periods of months). The most recent GCMs do well in representing the seasonal cycles on large scales, but their adequacy on regional scales still must be tested.

We are trying several approaches to test multiyear responsiveness of the models. Because such tests must cover extended periods or look at relatively small changes, these tests often are done with simplified models. Climate models are being used to investigate the climatic effects of recent volcanic eruptions and solar variations. Over much longer periods, we are trying to determine if the models can explain the causes of major glacial advances and retreats and past warmings. Initial test have been conducted, but further tests are needed to investigate the adequacy of representation of the oceans and cryosphere.

Despite much progress on these three approaches to model validation, there remain many areas where work is needed. First, there are important, unexplained differences among models and between models and data. Second, some model processes, such as the role of clouds in moderating or amplifying model sensitivity, have not been adequately tested. Third, model validation on regional and seasonal scales is still much too limited to be useful to those studying climate impacts. Fourth, the investigation of the ocean's role in controlling the rate of climate change is just beginning. Fifth, we are beginning to study approaches for modeling how the climate change develops over periods of decades rather than simply the change in "equilibrium" climate. Sixth, we need to recognize that the climate is responding not just to changes in CO_2, but also to changes in such things as trace gases, volcanoes, and deforestation. Although we are developing a sense of the change in equilibrium climates that may occur, we have a long way to go before we will be able to project how climate extremes, which have the most effect on societal structure, will change.

Ocean Response to CO_2 and Atmospheric Warming Oceans have an important role in the CO_2 problem because they are the ultimate sink for CO_2 produced by burning fossil fuel. The ocean-atmosphere coupling also determines the rate at which heat flows from the atmosphere to the ocean. Improved data and models are needed to address problems of CO_2 and heat transfer from atmosphere to oceans. Joint NSF-DOE research on Transient Tracers in Oceans has strengthened the data base for developing ocean circulation models. Existing ocean models, however, are inadequate representations of ocean circulation. While this joint research has been fruitful, more focused research is needed. This focused program will include: (1) measurements of the CO_2-inorganic-organic chemistry of water, (2) acquisition of gas exchange and tracer data, (3) coordination of model development with specific attention to data needs for multidimensional ocean circulation models, and (4) measurements and modeling of heat exchange for use with coupled ocean-climate models.

Trace Gases Initiative. Recent studies indicate that trace gases (e.g., methane, freons, nitrous oxide, and ozone) can have a combined climate effect ranging from half to equal that of the CO_2-induced climate effect. Such an effect is not only important in its own right but complicates detecting and predicting the magnitude and the rate of CO_2-induced climate change. As a result, the DOE has requested an additional $1 million in the FY 1985 budget (over the enacted FY 1984 budget level) to study atmospheric trace gases. The objective is to attain a perspective on the trace gases issue in relation to the carbon dioxide problem.

This effort will not answer all the questions on trace gases. It will, however, allow us to begin to investigate the uncertainties. For example, there is no historical record for the trace gases comparable to that for CO_2. The DOE is working with the National Climate Program Office to coordinate our trace gas study effort with related programs at the NSF, NASA, NOAA, and EPA.

Indirect Effects. Our major effort to date has been research on the direct effects of increased CO_2 concentration in the atmosphere: climate change and vegetation response. We are now starting research on the indirect effects of CO_2 increases. We have selected agriculture, forestry, water resources, human health, and fisheries for case studies or for regional documentation and analyses. Our objective is to document the data required to do meaningful cost/benefit analyses.

Sea Level. Considerable publicity and international concern surrounds the issue of sea level rise from CO_2-induced climate change. Estimates from recent reports vary from a 70 cm rise (a little less than 2 1/2 feet) in 100 years to as high as a 345 cm rise (a little more than 11 feet) by the year 2100. These estimates have been derived by examining the sea level record for the past 100 years, attributing the observed rise to such processes as ocean thermal expansion and ice melt, and using linear relationships to project these processes into the future. The estimates imply massive melting of ice; but many glaciologists point out that there is no reason to support such direct relationships. Uncertainties of ice-climate relationships are so large that the sea level could even fall because of increased precipitation in the polar regions from a CO_2-induced climate change. The collapse of the West Antarctic ice sheet has the potential for causing a 5-6 meter (16-20 ft.) sea level rise. However, glaciologists caution that predictions of a sudden and catastrophic rise in world sea levels due to CO_2-induced warming of this ice sheet are unfounded.

In our evaluation of the CO_2-climate/sea level issue, we have concluded that the research now underway or planned will greatly improve our understanding in this important area. For example, the National Science Foundation is supporting a 3-year research program, carried out by four institutions, which is the most intensive study yet undertaken on ice behavior and the relationship between the stability of the West Antarctic ice sheet and global climate. Additionally, the National Academy of Sciences is planning a study that should produce a definitive report on sea level change and global climate.

Plans for Statements of Progress

Spending for the National Program on Carbon Dioxide-Climate now exceeds $20 million per year among the six agencies involved. At this rate, by the end of fiscal year 1984 the Federal government will have spent more than $100 million on this topic since 1978.

The Department is preparing a series of reports, as an accounting of this effort. These State-of-the-Art reports are being prepared and will be ready for release in early 1985. The reports will reflect the results of a great variety of research efforts. Government and non-Government, basic and applied, foreign and domestic.

Scope of the State-of-the-Art Reports. These reports will present the most current and comprehensive statement possible of the knowns, unknowns, and uncertainties involved with the research data in each of five major research areas. Specific topics to be covered by the reports will include the global carbon cycle, detection of CO_2-induced climate change, climate modeling, direct response of vegetation to increased CO_2 levels, and the indirect effects.

These reports will represent a significant milestone in the Carbon Dioxide Research Program. They are intended to communicate to the broader scientific community the current state of our research and progress to date in each major area. A central theme will be traceability via references for results, assumptions, and uncertainties in the findings. The writing of each report is being coordinated and edited by experts in the specific research area concerned. There are a total of 75 authors representing 55 different institutions and 6 countries.

American Association for the Advancement of Science (AAAS) Review. As part of a stringent quality control process, the DOE has arranged for the AAAS to review and critique the reports. Each chapter will be anonymously peer reviewed. This process will ensure that the reports reflect the full range of views regarding the current state of knowledge and that no important research has been overlooked.

The Statement of Findings. By the summer/fall of 1985, a Statement of Findings will be puhished. This report will synthesize the State-of-the-Art reports and other studies and present an integrated, systems view of the entire research program needed to reduce uncertainties. The report is expected to provide a comprehensive state-of-knowledge discussion of the potential long-term implications of increasing levels of CO_2 rather than definitive recommendations pertaining to amelioration policies and strategies.

Summary

It is the goal of the Department of Energy to provide a base of facts such that environmental decisions and actions can be based on solid understanding. Studies done to date have led to a much improved understanding of the role of carbon dioxide in the global environment. More research is still needed before policy decisions pertaining to national and international strategies for ameliorating potential adverse effects can be made. We are pleased that our goal was also stressed by the Carbon Dioxide Assessment Committee of the National Academy of Sciences.

In short, at this time we know that change can be expected, but we do not know the timing, location or magnitude. We must concentrate on improving our knowledge base before we can make meaningful impact assessments, plan strategies for modification, adaptation and prevention, or develop policy options for consideration. The DOE's role in this national effort at this time is to improve the knowledge base.

Mr. GORE. Well, again I apologize for the fact that we are under such severe time constraints and for the fact that earlier witnesses absorbed our attention so much that we ate up some of the time we should have spent with you.

Let me just ask one question, and I will save the others for the record: You are requesting $13.418 million for the CO_2 budget this fiscal year as opposed to $12.5 last year. Do you have figures on the total national climate program? It was $24.563 last fiscal year. What's it going to be this year? Do you know?

Dr. KANE. Do you have those numbers?

Mr. KOOMANOFF. No, we have not received those numbers as yet. We go out to each of the sister agencies and ask them what their budgets are and since we are all going through the budget cycle right now, no one wants to commit exactly what will be spent in those areas until the budget has been approved by the Congress. As soon as that is done, like the other data that we have supplied, we will be able to supply it not only by agency but by what region.

[The following was supplied for the record:]

National program on carbon dioxide—climate

[In thousands of dollars by fiscal year]

	Estimate 1985
Department of Engery	$13,418
National Science Foundation	6,718
National Oceanic and Atmospheric Administration	1,961
Department of Agriculture	2,923
Department of Interior	215
Total	25,235

Mr. GORE. Very good. OK.

Again, I wish we could spend more time, but I am grateful for your prepared statement and the answers you are going to provide. I think it has been a very interesting hearing. I would like to thank all of the witnesses. With that, we will stand adjourned.

[Whereupon, at 12:56 p.m., the subcommittees recessed, to reconvene at the call of the Chair.]

[Questions and answers submitted for the record by Dr. Kane follow:]

Department of Energy
Washington, D.C. 20585

March 30, 1984

Ms. Betty Eastman
Committee on Science and Technology
Subcommittee on Investigations
and Oversight
House of Representatives
Washington, D.C. 20515

Dear Ms. Eastman:

On February 28, 1984, Dr. James S. Kane, Deputy Director of the Office of Energy Research, appeared before the Subcommittee on Investigations and Oversight and the Subcommittee on Natural Resources, Agriculture Research and Environment of the Science and Technology Committee to discuss carbon dioxide and the greenhouse effect.

Following that hearing, the Committees submitted written questions for response to supplement the record. Enclosed are the answers to those questions.

If you have any questions, please call Ingrid Nelson or Tom Pretorius of my staff on 252-4277. They will be happy to assist you.

Sincerely,

Thomas H Pretorius

for Robert G. Rabben
Assistant General Counsel
for Legislation

Enclosure

POST HEARING QUESTIONS AND ANSWERS

RELATING TO THE

FEBRUARY 28, 1984, HEARING

BEFORE THE

SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT

AND THE

SUBCOMMITTEE ON NATURAL RESOURCES, AGRICULTURE RESEARCH AND ENVIRONMENT

COMMITTEE ON SCIENCE AND TECHNOLOGY

U.S. HOUSE OF REPRESENTATIVES

WITNESS: DR. J. KANE

QUESTIONS FOR
DR. JAMES S. KANE
DEPARTMENT OF ENERGY

RESEARCH TIMETABLE

Question 1A: On page 2 of the testimony you state, "We agree with the academy position that increased scientific understanding of CO_2 is needed. Their conclusion is reasonable: We have time to conduct the needed research." On the other hand, the EPA report is not so optimistic. What scientific evidence has lead you to conclude that there is adequate time to conduct the necessary research?

Answer: Previous analyses have shown a steady exponential growth of global CO_2 production at 4.3 percent per year. With the exception of the two world wars and the great economic depression of the 1930s, this growth rate appeared to persist back to 1860. Recent analyses by the Institute for Energy Analysis, Oak Ridge Associated Universities, however, have shown that for the period 1973-1983 the rate of growth averaged only 1.86 percent per year, a significant decrease. 1973 is the year when pricing of the world's oil supplies underwent major changes causing consumers to reevaluate their needs for oil. This is evidence that the fossil fuel era has undergone fundamental changes; rates of growth of CO_2 emissions that were possible with "cheap energy" are unlikely in the future. As a consequence, most recent estimates of future global energy requirements now project energy growth rates in the 0.8-2.6 percent range for the next 100 years. If one chooses a mid value of growth, for example, 1.5%, this slower rate of CO_2 emission, if sustained, is very important to the carbon dioxide issue because atmospheric buildup of carbon dioxide will occur more slowly thus CO_2 doubling time is extended to 80 years from now. This longer time to doubling allows more time to investigate climate and other possible consequences of increasing carbon dioxide. Another important piece of evidence is a new estimate of 19th century CO_2 reached at a recent World Meteorological Organization meeting of experts. The new estimate is in the range of 260 to 280 ppm. This new estimate has important implications for effects on climate. The previously accepted estimate for the preindustrial CO_2 level was 295 ppm. The increase from the new level for preindustrial CO_2, 260 to 280 ppm, to the current 340 ppm level over the last 100 to 150 years constrains climate model predictions of global average temperature. Using the previous estimates for CO_2-level changes, the global average temperature increase would range from 1.5° to 4.5°C. Using the new estimate, the upper limit of the temperature range is reduced substantially from 4.5° to 3°C.

Question 1B. Some testimony presented in today's hearing points out that the impact of the greenhouse effect is being felt today. Doesn't this indicate that we should accelerate the research program in case the academy's and your position are too conservative?

Answer: The Department of Energy believes there is no firm evidence to support the statement that the impact of the greenhouse effect is being felt today. For example, the observed temperature change over the past 100 years is not inconsistent with the direction of CO_2 change and model projection, however, since the observed temperature change is still under the range of natural variability, we can not clearly distinguish what we would call a CO_2-induced climate change. Other changes, such as sea level, are also not inconsistent with projected changes, but they are all within natural variability and we still do not have a clear cause and effect relationship. In regard to accelerating the research program, we believe the appropriate time for decisions of this nature would be following publication in 1985 of the state-of-the-art and statement of findings reports described in the testimony. The aim of this effort is to present an integrated, systems view of the entire research program needed to reduce uncertainties.

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PREINDUSTRIAL CO_2 LEVEL

Question 2A. On page 4 you state that a new estimate of 19th century CO_2 was made placing the range at between 260 to 280 parts per million (PPM). The previously accepted estimate for the preindustrial CO_2 level was 295 ppm. Further, you indicate that this information would have the effect of reducing the upper bound of the temperature increase, from the greenhouse effect, from 4.5 to 3 degrees centigrade. It would appear that if there were less CO_2 in the 19th century then it indicates that the rate of increasing atmospheric concentration is even greater than previously thought. This would indicate that the problem is even more serious than originally believed. Would you comment on this please?

Answer: One of the earlier witnesses stated that one solid boundary condition was worth 1000 hours of computer time. A firm measurement of the 19th century atmosphere CO_2 level provides such a key boundary condition for climate modeling and carbon cycle modeling. For example, if I select the 260 ppm as the 19th century CO_2 level, then over the last hundred years CO_2 has increased 80 ppm instead of 45 ppm. The observed temperature increase over the last hundred years is about 0.3 to 0.5°C. This boundary condition and observed temperature change are more consistent with models predicting a 1.5 to 3°C temperature change for a doubling of CO_2 than models predicting an increase above 3°C. This means climate is most likely less sensitive than first thought. We still need to examine why some models predict higher sensitivities. For example clouds can act to increase or decrease temperature. Currently, the majority of models suggest an overall neutral effect. The oceans can slow the response causing a lag of 10-25 years. One researcher claims a 100 year ocean lag. That would mean that the 4.5°C increase would not be inconsistent with the observed change in CO_2 and temperature. The working consensus is that the 100 years is not valid, but the argument must be presented in the science process and stand or fall on its own merit.

I believe that this confirms that the models are sufficient to give us the direction of the temperature change, not the rate of change or regional distribution of change.

Question-2B: Based on the new estimate that the maximum temperature warming, when the CO_2 level is doubled, is 3 degrees centigrade, does this mean that the impact of the greenhouse effect is not as serious as originally thought?

Answer: No. A 1.5 to 3°C temperature increase would be serious. For example, paleoclimate records show that a 1°-2° shift in mean is associated with precipitation changes that would have serious affects on agriculture. The new results suggest climate is less sensitive to increased CO_2. In other words, we may experience less of a climate change for a given increase in CO_2. This translates into increased time for research on the rate, magnitude and geographic distribution of climate change. Also, the additional time allows increased flexibility in our responses. For example, genetic engineering for agriculture may allow us to accept and take advantage of a larger change in climate than we could do otherwise.

CO_2 EFFECT ON CROPS

Question 3A: On page 6 you describe a series of experiments with plants grown in CO_2 controlled greenhouses. The research results indicate that the CO_2 stimulates plant growth. Did these experiments take into consideration the changes in climate, temperature or water? If not, aren't these results very preliminary at best?

Answer: These results emphasize direct effects of CO_2 on plant photosynthesis and growth, and were obtained using open-top chambers and soil-plant-atmosphere designs for precise control of atmospheric CO_2. These approaches have produced unique field-type data on yield of a harvestable product for conditions of conventional cultivation practice, natural sunlight and ambient temperature-precipitation-humidity-wind conditions. Such conditions are considered more realistic than controlled greenhouses and simultaneously treat the range of environmental variables that crops normally experience. The experimental approaches are providing meaningful data on the direct effects of CO_2 on yield of corn and soybeans at four different geographic locations. They are Raleigh, North Carolina, Gainesville, Florida, Mississippi State, Mississippi, and Livermore, California, which illustrate a range of temperature and precipitation environments.

The normal diurnal variation of temperature and water stress occurred with these experiments. In a few instances, severe water stress was experimentally imposed on the crops with the result that elevated CO_2 compensated for detrimental effects of water stress. This response is preliminary and needs further confirmation with other crops; yet it is an important finding because it means that by some mechanism CO_2 tends to alleviate suppressed growth due to water stress. This direct CO_2 effect may compensate for detrimental effects of temperature and soil moisture stress related to climate - weather changes whatever the causes may be. This research is providing crop yield data for experimental conditions of elevated CO_2, <u>and</u> for normal conditions of crop growth; experiments are continuing to examine effects of elevated CO_2 on water use. Additional research is needed to determine relationship between CO_2 stimulated plant growth and requirements for other nutrients, such as nitrogen and phosphorous.

Question 3B: Based on the research results as outlined in your testimony the conclusion could be drawn that the greenhouse effect is beneficial for crops. When climate, temperature and water supply are considered, the exact opposite conclusion is reached. Would you comment on this please?

Answer: All evidence supports the premise that CO_2 directly enhances photosynthesis and crop growth. While it is not yet possible to specify regional climate change attributable to CO_2, warmer temperatures and less rainfall may indirectly affect crop productivity in areas where these climate variables are currently <u>marginal</u>. For example, crop productivity may decrease near semi-arid margins and possibly increase or not be affected at all near wet margins. If regional climate change occurs, different crops may be grown in a given region, or growth of a particular crop may shift to a region of more optimal climate. Thus, adaptation is anticipated both in terms of using new species and varieties, including development of new forms from plant breeding and genetic engineering, and in terms of shifts of agriculture production centers. Given the limited state of knowledge about possible regional climate change, and considering normal practices of adapting crops to climate zones, the consequences for crop production are uncertain. The principal unknown for which more data is needed is the direct effect of CO_2. Once this information is available, and once regional climate change can be specified, then it may be possible to analyze comprehensive effects of altered CO_2, temperature, precipitation and other climate related variables. Meantime, research is devoted to data acquisition and improvement of crop and climate models.

CLIMATE STUDIES

Question 4A: On page 7 you discuss, under unresolved issues, the need for better climate modeling. Based on the testimony of other witnesses, this is an important research area. What is the level of funding for the DOE climate studies?

Answer: We are spending about $3.1 million in FY 1984. In FY 1985 about the same amount will be spent plus the requested increase for trace gases. The program is documented in the DOE plan - CO_2 Climate Research Plan, December 1983 copies of which have been sent to your office. The program is divided into three areas: climate modeling, first detection and supporting climate data and analysis. Climate modeling includes extending, verifying, and applying climate system models for use in estimating the climatic effects of increasing CO_2 concentrations. This work also will provide guidance for first detection of climatic effects and assessments of societal, biological and economic impacts. We are spending $1.6 million on climate modeling. First detection involves evaluating and analyzing data in search of evidence that the predicted CO_2-induced climate changes are in fact occurring. Analyses of trends in trace gases and aerosols also may be required, as well as variations in solar activity and IR radiation. About $0.6 million is spent on this effort.

Supporting Climate Data and Analysis includes searching historic and paleoclimatic records for evidence of different climates, particularly those warmer than the present, that can be used to study the mechanisms of climate change, to determine the ranges of past variations, and to develop analogs of possible CO_2-induced warmer, and warming, climates and supply key data sets for climate modeling and first detection. This effort also brings the information generated by the three areas together into a statement of what we know and do not know about CO_2 induced climate change. About $0.9 million is spent in this area.

Question 4B: Is your research efforts coordinated with NOAA and NASA? Please explain.

Answer: Yes. We coordinate with the NOAA, NSF, NASA and other Federal agencies through the National Climate Policy Board and other interagency committees on climate, meteorology, and oceanography. Our plans are coordinated both through the formal boards and directly on a colleague to colleague basis.

Proposals and technical reports receive programmatic and technical review. These are circulated for review and coordination to agencies that have similar programs and interests. We also receive proposals for coordination. This coordination often results in direct joint funding of projects such as the DOE-NSF Transient Tracers in Oceans project and the DOE-NSF climate modeling at the National Center for Atmospheric Research. We also have joint projects with NOAA and NBS.

SEA LEVEL RISE

Question 5A. On page 11 you indicate that the projected sea level rise, due to doubling of the CO_2 concentration, ranges from approximately 2 1/2 feet to over 11 feet by the year 2100. Is the DOE research program adequate to provide the necessary data to show which sea level rise is accurate?

Answer: Sea level may change due to a carbon dioxide-induced climate change. Potentially the greatest threat is the disintegration of the We Antarctic ice sheet which could raise global sea level by five meters .. feet. Speculation as to the time involved ranges from 200 to 500 years and beyond, if at all. The uncertainty is great because little is known about the ice sheet itself and its interactions with the ocean and climate.

In response to this situation, the DOE sponsored a workshop in 1980 on the subject to promote a discussion of the research problems involved and to develop specific projects to solve these problems. A summary report was published by DOE.

It is national policy that the National Science Foundation shall budget for and manage the entire United States national program in Antarctica. In 1983 the NSF initiated a 3-year effort in West Antarctica which will be the most intensive study yet on ice behavior and the relationship between the stability of the ice sheet and its interaction with global climate.

The DOE sees as its responsibility the support of high priority research needs not covered by the NSF. For example, the DOE sponsored the National Academy of Sciences to conduct a workshop to bring global circulation modelers and glaciologists together to press for improvement of current simulations of the existing polar climate as a prelude for predicting a concrete CO_2 scenario for West Antarctica. The report will state "Firm quantitative predictions for the future of West Antarctica, therefore, cannot be attempted, at the present state of knowledge." DOE initiated a contract with one of the top glaciological modeling groups to examine the breakup potential of the West

Antarctic ice sheet and to provide a fundamentally different approach to the only other ice sheet modeling effort sponsored by NSF. We also supplemented an NSF project studying the circulation and characteristics of the Ross Sea. This supplement brought this top priority project up to its intended optimum level of effort. DOE commissioned a paper on the health and prognosis of the West Antarctic ice sheet by one of the nation's leading glaciologists.

The most critical research and monitoring need for a polar orbiting satellite with a laser altimeter is, unfortunately, not in the planning stages of any Federal agency.

Even if the West Antarctic ice sheet never disintegrates, sea level may still change due to carbon dioxide-induced climate change. Positive changes may result from thermal expansion and/or ablation of polar ice sheets and mountain glaciers or negative changes may result from a net accumulation of ice due to increased snowfall on the ice sheets. Even less is known about all these processes including whether the sea level has in fact changed in the past century and if so how much and the causes of such a change.

To examine these last two uncertainties, the DOE, through the Lawrence Livermore National Laboratory, contracted for three reports on sea level change and its possible causes. The reports conclude that the uncertainties remain largely because the data sets available are inadequate for the task. In regard to thermal expansion, the NAS carbon dioxide assessment report cautioned that there is no good understanding of heat transport to the deep ocean but that major ongoing research efforts such as the projected World Ocean Circulation Experiment are directed at remedying this unsatisfactory situation.

Ablation of polar ice sheets, the potential contribution to sea level of mountain glacier and research needs was a topic for discussion at the December

1983 meeting of the Committee on Glaciology of the Polar Research Board at the urging of the DOE.

Finally, to pull together all that is known on the overall question of sea level change due to a carbon dioxide-induced climate change, the DOE is considering a proposal by the National Academy of Sciences to sponsor a meeting of experts in mid 1984. The product would be a statement of knowledge on the subject to be published in late 1984 in conjunction with the DOE prepared state-of-the-art reports on the major programs comprising the national carbon dioxide research effort.

In summary, the Federal research program is well suited for improving knowledge on this topic.

Question 5B: What is the current level of funding for research that is studying the sea level rise?

Answer: In fiscal year 1983, the level of Federal funding for research on CO_2-induced climate changes in the West Antarctic ice sheet and, the resulting impact on sea level totaled approximately $1.0 million. In FY 1984, this is expected to increase slightly. The majority of these funds come from the National Science Foundation. DOE funding in this area in FY 1984 is $0.4 million. Other research that contributes to knowledge in the sea level question, such as ocean heat flux, can not be separately identified as responding to the CO_2-induced climate change question.

Question 5C. When do you estimate that the research program will begin to provide accurate data on the rate of sea level rise?

Answer: We estimate it will take 10 years for a research program, sustained at the levels described in the above answer, to provide accurate data on projected sea level changes. Since projections depend so heavily on mass balance, net accumulation of snow and ice on polar ice sheets, calculations, this estimate could be reduced significantly, to a few years, if a polar orbiting satellite equipped with a laser altimeter was available.

CO_2 RESEARCH PROGRAM

Question 6A. One of the witnesses presented testimony that the DOE CO_2 program "has been too intent on short term goals." He further stated that "DOE support has been too small, too focused and too 'mission oriented'. The CO_2-climate issue is a scientific, not an engineering problem and the DOE has not approached the research correctly." Does the DOE CO_2 program have 5 and 10 year goals? Please explain.

Answer: The Department of Energy has prepared Research Plans which contain general program goals and specific scientific objectives. The plans have various timetables for obtaining data, developing models, answering questions, but in no case are the plans organized around 5-year and 10-year goals. In some cases the timetables call for information in 2 to 3 years; in other cases 10 to 15 years, or possibly longer, will be required to reduce uncertainty. It should be fully appreciated, however, that the research questions are well-defined, and candidate approaches are identified for getting information and answering questions. The development of research plans began with a series of scientific workshops and conferences, for example, Miami Beach, 1977; and over the past several years the plans have been reviewed, amended, updated based upon the input of scientists, federal agencies and international groups and sent to the Congress. The plans explicitly invite broad participation by the science community. There is no validity to the criticism that "the DOE Program has been too intent on short-term goals," and that "the DOE has not approached the research correctly." DOE regards the CO_2 issue as an international problem requiring much more scientific data and analysis. The scientific community, U.S. and international, have been involved in all of our activities.

Question 6B. Is the DOE CO_2 program too mission oriented?

Answer: If we define "mission oriented," to mean directed actions towards achieving objectives and obtaining answers to scientific questions, the DOE CO_2 program is indeed mission oriented. The mission is to define objectives, to focus activities on getting answers in a timely fashion, and to obtain research results needed to support energy policy decisions.

QUESTIONS FOR
DR. JAMES S. KANE
DEPARTMENT OF ENERGY

RESEARCH TIMETABLE

1. ON PAGE 2 OF THE TESTIMONY YOU STATE, "WE AGREE WITH THE ACADEMY POSITION THAT INCREASED SCIENTIFIC UNDERSTANDING OF CO2 IS NEEDED. THEIR CONCLUSION IS REASONABLE: WE HAVE TIME TO CONDUCT THE NEEDED RESEARCH." ON THE OTHER HAND, THE EPA REPORT IS NOT SO OPTIMISTIC.
   A. WHAT SCIENTIFIC EVIDENCE HAS LEAD YOU TO CONCLUDE THAT THERE IS ADEQUATE TIME TO CONDUCT THE NECESSARY RESEARCH?
   B. SOME TESTIMONY PRESENTED IN TODAY'S HEARING POINTS OUT THAT THE IMPACT OF THE GREENHOUSE EFFECT IS BEING FELT TODAY. DOESN'T THIS INDICATE THAT WE SHOULD ACCELERATE THE RESEARCH PROGRAM IN CASE THE ACADEMY.S AND YOUR POSITION ARE TOO CONSERVATIVE?

PREINDUSTRIAL CO2 LEVEL

2. ON PAGE 4 YOU STATE THAT A NEW ESTIMATE OF 19TH CENTURY CO2 WAS MADE PLACING THE RANGE AT BETWEEN 260 TO 280 PARTS PER MILLION (PPM).THE PREVIOUSLY ACCEPTED ESTIMATE FOR THE PREINDUSTRIAL CO2 LEVEL WAS 295 PPM. FURTHER, YOU INDICATE THAT THIS INFORMATION WOULD HAVE THE EFFECT OF REDUCING THE UPPER BOUND OF THE TEMPERATURE INCREASE, FROM THE GREENHOUSE EFFECT, FROM 4.5 TO 3 DEGREES CENTIGRADE.
   A. IT WOULD APPEAR THAT IF THERE WERE LESS CO2 IN THE 19TH CENTURY THEN IT INDICATES THAT THE RATE OF INCREASING ATMOSPHERIC CONCENTRATION IS EVEN GREATER THAN PREVIOUSLY THOUGHT. THIS WOULD INDICATE THAT THE PROBLEM IS EVEN MORE SERIOUS THAN ORIGINALLY BELIEVED. WOULD YOU COMMENT ON THIS PLEASE?
   B. BASED ON THE NEW ESTIMATE THAT THE MAXIMUM TEMPERATURE

WARMING, WHEN THE CO_2 LEVEL IS DOUBLED, IS 3 DEGREES CENTIGRADE, DOES THIS MEAN THAT THE IMPACT OF THE GREENHOUSE EFFECT IS NOT AS SERIOUS AS ORIGINALLY THOUGHT?

CO_2 EFFECT ON CROPS

3. ON PAGE 6 YOU DESCRIBE A SERIES OF EXPERIMENTS WITH PLANTS GROWN IN CO_2 CONTROLLED GREENHOUSES. THE RESEARCH RESULTS INDICATE THAT THE CO_2 STIMULATES PLANT GROWTH.
   A. DID THESE EXPERIMENTS TAKE INTO CONSIDERATION THE CHANGES IN CLIMATE, TEMPERATURE OR WATER? IF NOT, AREN'T THESE RESULTS VERY PRELIMINARY AT BEST?
   B. BASED ON THE RESEARCH RESULTS AS OUTLINED IN YOUR TESTIMONY THE CONCLUSION COULD BE DRAWN THAT THE GREENHOUSE EFFECT IS BENEFICIAL FOR CROPS. WHEN CLIMATE, TEMPERATURE AND WATER SUPPLY ARE CONSIDERED, THE EXACT OPPOSITE CONCLUSION IS REACHED. WOULD YOU COMMENT ON THIS PLEASE?

CLIMATE STUDIES

4. ON PAGE 7 YOU DISCUSS, UNDER UNRESOLVED ISSUES, THE NEED FOR BETTER CLIMATE MODELING. BASED ON THE TESTIMONY OF OTHER WITNESSES, THIS IS AN IMPORTANT RESEARCH AREA.
   A. WHAT IS THE LEVEL OF FUNDING FOR THE DOE CLIMATE STUDIES?
   B. IS YOUR RESEARCH EFFORTS COORDINATED WITH NOAA AND NASA? PLEASE EXPLAIN.

SEA LEVEL RISE

5. ON PAGE LL YOU INDICATE THAT THE PROJECTED SEA LEVEL RISE, DUE TO DOUBLING OF THE CO_2 CONCENTRATION, RANGES FROM APPROXIMATELY 2 1/2 FEET TO OVER 11 FEET BY THE YEAR 2100.
   A. IS THE DOE RESEARCH PROGRAM ADEQUATE TO PROVIDE THE NECESSARY DATA TO SHOW WHICH SEA LEVEL RISE IS ACCURATE?
   B. WHAT IS THE CURRENT LEVEL OF FUNDIN[illegible] OR RESEARCH THAT IS STUDYING THE SEA LEVEL RISE?
   C. WHEN DO YOU ESTIMATE THAT THE RES[illegible] PROGRAM WILL BEGIN TO PROVIDE ACCURATE DATA ON THE RATE [illegible] SEA LEVEL RISE?

CO_2 RESEARCH PROGRAM

6. ONE OF THE WITNESSES PRESENTED TESTIMONY THAT THE DOE CO_2 PROGRAM "HAS BEEN TOO INTENT ON SHORT TERM GOALS." HE FURTHER STATED THAT "DOE SUPPORT HAS BEEN TOO SMALL, TOO FOCUSSED AND TOO 'MISSION ORIENTED'. THE CO_2-CLIMATE ISSUE IS A SCIENTIFIC, NOT AN ENGINEERING PROBLEM AND THE DOE HAS NOT APPROACHED THE RESEARCH CORRECTLY."
   A. DOES THE DOE CO_2 PROGRAM HAVE 5 AND LO YEAR GOALS? PLEASE EXPLAIN.
   B. IS THE DOE CO_2 PROGRAM TOO MISSION ORIENTED?