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# GLOBAL CHANGE RESEARCH: THE ROLE OF CLOUDS IN CLIMATE CHANGE

## HEARING

BEFORE THE

## COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION UNITED STATES SENATE

ONE HUNDRED SECOND CONGRESS

FIRST SESSION

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# GLOBAL CHANGE RESEARCH: THE ROLE OF CLOUDS IN CLIMATE CHANGE

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**MONDAY, OCTOBER 7, 1991**

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
*Washington, DC.*

The committee met, pursuant to notice at 9:41 a.m. in room SR-253, Russell Senate Office Building, Hon. Al Gore presiding.

Staff members assigned to this hearing: Anthony D. Socci and Mike R. Nelson, professional staff members; Louis C. Whitsett, minority counsel.

## OPENING STATEMENT OF SENATOR GORE

Senator GORE. Ladies and gentlemen, our hearing will come to order.

This is a little different than a normal hearing, in this sense. The Science, Space, and Technology Subcommittee has begun with this proceeding this morning, to systematically investigate a series of questions which involve important uncertainties related to global warming and what many of us believe is a generalized global environmental crisis, in order to improve our understanding of what is happening to the global environment.

And in order to search for increased consensus that in fact there is a problem which needs to be addressed, it seems worthwhile to look at the areas where much of the remaining uncertainty lies. Perhaps the single most important area of uncertainty involves the role played by clouds and water vapor in magnifying the greenhouse effect when additional greenhouse gases, including principally $CO_2$, are added to the atmosphere by anthropogenic means.

Many people are surprised when they examine the inner workings of the global climate models to discover that greenhouse gases like $CO_2$, actually play a relatively small role directly in warming the Earth. However, according to the models, the gases exert enormous leverage on the warming caused by water vapor, by increasing the amount of water vapor in the atmosphere.

The role played by clouds, however, in modifying the distribution of water vapor vertically and laterally throughout the global atmosphere introduces a number of uncertainties which have been incorporated, with greater and lesser success, into various models used to study global warming. We are, therefore, going to look at this area of major uncertainty.

There is another way in which this hearing today is different, the first way being that it is aimed at a level of detail that is finer, in detail, than the normal subject of inquiry for a Senate commit-

tee. The second difference in this proceeding is that it is a roundtable discussion, rather than a sequence of questions and answers solicited from each witness,in succession.

I do not know how this is going to work, but I ask for the cooperation of all of our witnesses this morning in seeking to extract from this process as great a contribution to the Senate's understanding of this subject as is possible.

In the Senate itself there is a rule whereby every Senator who stands to speak on the Senate floor addresses himself or herself to the Chair, and that is not to be excessively formal. It is because 200 years of experience has shown the Senate that it is a way to avoid fistfights, while maintaining order, decorum, and structure with respect to the discussion at hand.

Even though there is hardly any danger of fistfights this morning, if we could follow the same rule, even though it seems a little formal, I think it will provide more organization of the discussion. I assure you that I want to keep a free-flowing and open discussion to get the maximum interchange among you.

One disadvantage of this format, which some would regard as an advantage, is to deemphasize the formal opening statements. I have read all of your opening statements, with the exception of a couple of witnesses who did not get their formal statements in to the subcommittee in advance. I believe I am, nonetheless, familiar with the views of those witnesses.

All of the formal statements will be printed in full in the transcript of the proceeding. So, please assume that the committee is cognizant of all of the opening statements.

But by way of initiating the discussion, I am going to ask everyone to give an abbreviated version of what you believe is the most important message you want to deliver in your opening comments. Then we shall open up the discussion to topics at hand. These opening comments I would ask you to hold to a length of 3 minutes.

Well, I guess I should start by putting my opening statement in the record.

One other thing that I did not mention. We are very pleased to have among the witnesses, representatives of the agencies that have responsibility for the research topic at hand. This committee has the responsibility of authorizing funding for this enormous research program and we, therefore, have an interest in making certain that the priorities within that program are established correctly.

I am going to assume that this panel will at the conclusion of today's proceeding be unanimous in agreeing that clouds and water vapor research deserve the highest priority. But I also want to ask you to think about how we can better direct our effort so as to focus on the questions that are most important.

I am really pleased that the officials in charge of that research program will have the benefit of hearing this interchange as well, so that we can come to a meeting of the minds in subsequent discussions about how we can improve the research program.

Well, I will put the rest of my statement in the record.

[The prepared statement of Senator Gore follows:]



PREPARED STATEMENT OF SENATOR GORE

Good morning. Today, the Commerce Committee will examine some of the latest research on one of the key scientific questions regarding global change—the role of clouds. Clouds play a key role in global warming, the worst environmental threat we face. It has the potential to fundamentally alter our lives, the lives of our children and grandchildren, and every generation to follow. According to the best available scientific analysis, over the next hundred years there could be radical shifts in weather patterns and disruption of ecosystems, with some of the world's most productive farmland turned to desert and low-lying coastal areas around the world flooded.

Confronting this threat will require major changes in energy use, agriculture, transportation, and other activities worldwide. it will require an international commitment to slow the emission of greenhouse gases into the atmosphere, and if that commitment is not made now, the consequences later will demand even more. Making intelligent choices on how to deal with global warming will require the best scientific information available on the causes and effects of global warming.

To provide estimates of the extent and timing of global warming, researchers are using some of the world's most powerful supercomputers to build general circulation models. These models predict that the earth's temperature will increase between 1.5 and 4.5 degrees Celsius by the end of the next century. But the different models do not all agree, particularly when it comes to predicting local and regional climate changes.

One of the main reasons for these discrepancies is that different models treat clouds differently. Clouds play a fundamental role in the Earth's heat budget. Researchers have found that high-altitude clouds can act like an insulating blanket, amplifying the warming due to greenhouse gas accumulation. On the other hand, clouds can also reflect incoming solar radiation and thereby decrease warming.

Today, we will examine the different approaches that modelers are using and how they might be improved so that uncertainties in the models can be reduced. Doing that will require research on many different scales, from microscopic to global. The scientists here today are at the forefront of that research.

In addition to examining the latest research on clouds, we have representatives from NASA, NOAA, and the Air Force to discuss how their agencies have and will contribute to our understanding of global warming.

It is unusual for the Congress to focus in such detail on a complicated scientific question like the one we are considering today. But I believe it is essential that we understand thoroughly what the science can tell us and what it can't so that we can effectively meet the threat of global warming.

Today, we will not be using the standard hearing format. Rather than having panels of witnesses, I have asked everyone to join in a roundtable discussion. This will ensure a free and open exchange on the various scientific questions that researchers are trying to answer and help us all see clearly where there is general agreement and where there is disagreement in the scientific community.

In the coming months, I hope to conduct similar hearings on some of the other key scientific issues regarding global change. Last year, the Federal government spent almost one billion dollars on global change research, and I feel it is critically important that this Committee and the entire Congress keep abreast of the work being done.

I want to welcome our witnesses and thank them for being here today. Many of them have come a long way and rearranged very busy schedules to join us and I want to thank you all.

To begin the discussion, I think it would be most useful if we just went around the table and had everyone briefly introduce themselves and quickly summarize their research. Since we have so many people here today, I would ask you to try to hold your remarks to about three minutes. I guarantee you that we will have a lot of time to get into the details later.

Senator GORE. Mr. Chairman, your remarks, sir.

## OPENING STATEMENT OF SENATOR HOLLINGS

The CHAIRMAN. Today the Commerce Committee is holding a hearing to investigate one of the key research questions regarding global warming—the role of clouds. Over the past few years, the committee has held a number of hearings on global climate change, and witnesses at those hearings have made it clear that there are

a number of factors that influence the Earth's climate, including clouds.

Researchers tell us that clouds have a profound effect on the Earth's climate and that even a small change in the type and distribution of clouds could change the global mean temperature significantly. For that reason, it is critically important that researchers constructing climate models for predicting global warming understand the chemistry and physics of clouds. Indeed, in the research plan for the U.S. Global Change Research Program, the agencies involved have identified the role of clouds as a top research priority.

However, clouds are not easily understood, as they are a complicated phenomenon. Clouds come in many different and varied forms—rain clouds, thunderheads, low-lying fog, and high-altitude cirrus. According to meteorologists, water in clouds can come in more than 10 different forms, from invisible water droplets to baseball-sized hailstones. To understand this complexity, researchers are doing studies all over the world, using tools provided by various Federal agencies. Satellites operated by the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the Department of Defense provide useful information on the distribution of clouds. The Tropical Oceans Global Atmosphere Program, directed by NOAA and the National Science Foundation, also provides important information on other atmospheric and oceanic processes and their impact on climate change.

Today's witnesses will discuss the meaning of the data that has been collected. I understand that some researchers argue that changes in the type and distribution of clouds due to greenhouse warming by and large will cancel out its effects. I also understand that other researchers are much more pessimistic about the impact of clouds on global warming. These and other findings will be examined closely today.

While it is clear that many uncertainties remain in this area, the issue of global warming must be addressed now. We cannot afford to wait until we have all the answers. Today's witnesses will be able to provide us with some answers as to the impact of clouds on global warming. I look forward to their testimony.

Thank you, Senator Gore.

Senator GORE. Thank you, Mr. Chairman.

Now, we will begin here and go around the table. All of you no doubt know each other. However, a brief introduction may be in order for our guests.

First of all, Dr. V. Ramanathan is the Alderson Professor of Ocean Sciences at the Scripps Institution of Oceanography, University of California, San Diego.

Dr. Albert Arking is a Senior Scientist with the NASA Goddard Space Flight Center in Greenbelt, MD.

Dr. Robert Cess is Professor of Atmospheric and Physical Sciences at the Institute for Atmospheric Sciences at the State University of New York at Stony Brook.

Dr. Robert Charlson is Professor of Atmospheric Sciences and Adjunct Professor of Chemistry at the University of Washington.



Dr. Richard Lindzen is the Alfred P. Sloan Professor of Meteorology at the Department of Earth, Atmospheric and Planetary Sciences at MIT.

Dr. William Rossow is a Physical Scientist at NASA Goddard in New York.

Dr. Kevin Trenberth is Head of Climate Analysis for the National Center for Atmospheric Research.

Dr. Alan K. Betts is a Meteorologist at Middlebury, VT, and a principal researcher on projects for various agencies, even though he is usually not affiliated with a university, as I understand it.

Dr. Michael Hall is Director of the Office of Global Programs at the National Oceanic and Atmospheric Administration at Silver Spring.

Dr. Shelby Tilford is Director of Earth Science and Applications at the Office of Space Science and Applications with NASA.

And Col. Robert Townsend is Chief of Weather Plans for the Directorate of Weather at the Headquarters of the United States Air Force, Department of Defense. As I mentioned to Colonel Townsend informally at the beginning of this hearing, I have been involved in another committee, the Armed Services Committee, in starting up a program called the Strategic Environmental Research and Development Program. This program seeks to make use of the assets of the U.S. military that could have value added. For example, in this case, there is the possibility of developing an instrument package that might be flown on routine missions by the Air Force all over the world, missions that would take place anyway.

All right, I have taken the longest of anybody, so let me without further ado, ask Dr. Ramanathan to introduce the topic for discussion.

## STATEMENT OF V. RAMANATHAN, Ph.D., ALDERSON PROFESSOR OF OCEAN SCIENCES, SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA AT SAN DIEGO

Dr. RAMANATHAN. Honorable Mr. Chairman, I thank you for the privilege and opportunity to testify before your committee.

My research focuses on the role of clouds and the atmospheric greenhouse effect on climate and climate change. In my written testimony I have summarized results from the Earth Radiation Budget Experiment, or ERBE for short. ERBE is a three-satellite experiment launched in 1984 by NASA. My testimony addresses three topics.

The first topic concerns the radiative effects of clouds on climate. The second concerns the atmospheric greenhouse effect on the role of water vapor feedback. And the third topic is the thermostat hypothesis proposed by Dr. Collins and I in the May 1991 issue of the British journal Nature.

Under each of these topics I describe the principal results, clarify its implications to global warming, and also clarify the confusions which have arisen out of the results.

If asked, I will be glad to elaborate on any one of these topics and even, if necessary, show the results.

[The prepared statement of Dr. Ramanathan follows:]

## Prepared Statement of V. Ramanathan

Honorable Mr. Chairman and the Honorable members of the committee: I thank you for the opportunity to address your committee. My research focuses on the role of the clouds and the atmospheric greenhouse effect on climate and climate change.

Water vapor and carbon dioxide are the most important atmospheric greenhouse gases that trap the thermal radiation emitted by the Earth's surface. Ozone and other trace gases contribute about 10 percent of the total trapping. This trapping effect by gases in the atmosphere is referred here as the *atmospheric greenhouse effect*. Clouds, like atmospheric gases, also trap thermal radiation and make an important contribution to the greenhouse effect of the planet. Clouds, in addition, reflect significant amount of solar radiation back to space, and determine the amount of solar energy absorbed by the surface-atmosphere system. The cloud reflection of incoming solar energy, which would tend to cool the climate is referred as the cloud shortwave forcing; * * * the greenhouse effect of clouds , which would tend to warm the climate, is the cloud longwave forcing; * * * the net effect of the two competing influences of clouds is referred as the cloud-radiative forcing.

The ERBE, which is a multi-satellite experiment launched in late 1984 by NASA, has yielded valuable insights into the atmospheric greenhouse effect and the cloud-radiative forcing. In this testimony, I will summarize the results relevant to the topic of this hearing, obtained by my colleagues Drs. B. Barkstrom, E. Harrison (both at the NASA Langley Research Center), Professor R.D. Cess (SUNY, Stony Brook) and my group. A more complete summary of the important ERBE results obtained by several other ERBE science team groups in the U.S., Germany and England can be obtained from Dr. Barkstrom who is the leader of the ERBE science team.

### I. CLOUD-RADIATIVE FORCING

Globally, clouds have a net radiative cooling effect on the present day climate. That is, the solar energy reflected by clouds exceeds their greenhouse effect. *Thus ERBE estimates that clouds have a net cooling effect on the present day climate.* The ERBE data also reveal that the cloud-radiative forcing vies significantly with latitude, longitude, seasons and from year to year. Scientists are using these variations to understand how the surface temperature distribution and atmospheric circulation patterns are linked with the radiative effects of clouds.

**Implications to Global Warming:** *The net cooling effect of clouds on the present day climate does not necessarily imply or even suggest that clouds will offset the global warming due to the increases in greenhouse gases.* For example, some of the climate models which predict a global warming of 2 to 4 C due to doubling of $CO_2$ also simulate the cooling effect of clouds on the model's control climate. The feedback effect of clouds on climate will depend upon how clouds and their radiative forcing will respond to global warming. These feedback effects are largely unknown at present. However, ERBE data reveal that the magnitude of the individual longwave and shortwave cloud forcing terms are so large that just a small change in these terms can have a substantial feedback effect.

**Impact on Global Climate Models:** The data are already having a substantial impact on three dimensional global climate models used in global warming studies. For example, the most recent generation of models developed at the National Center for Atmospheric Research (Drs. J. Kiehl & P. Rasch), Colorado State University (Dr. D. Randall) amongst several others, have used the ERBE cloud forcing data to validate and improve the treatment of clouds. In the next few years we should learn the impact of the improved cloud treatments on global warming predictions.

### II. ATMOSPHERIC GREENHOUSE EFFECT: THE ROLE OF WATER VAPOR FEEDBACK

Water vapor concentrations in the atmosphere vary significantly due to thermodynamic and dynamic processes such as convection and large scale circulation. As surface and atmospheric temperatures increase, the saturation vapor pressure of vapor increases significantly; for example, it increases by about 15 percent for a 3 C increase in temperature. As the saturation pressure increases, the vapor concentration should increase provided the dynamic processes do not offset this increase by, for example, offsetting the moistening in the lower altitudes with a large drying of the upper altitudes. Increases in the vapor concentrations will lead to increases in the trapping of thermal radiation. This thermodynamic theory for the positive coupling between temperature1 water vapor concentration and its atmospheric greenhouse effect (the so-called water vapor feedback) contributes to a significant positive amplification of the global warming predicted by climate models. If this thermodynamic theory represents a fundamental property of the Earth's climate, it should exist in



the present climate system as indeed confirmed by the ERBE data analyses by Raval and Ramanathan and by Professor G. Stephens of Colorado State University. ERBE data in conjunction with NOAA's sea surface temperature (SST) data have been used to estimate the thermal radiation trapped by the atmosphere over oceanic regions. From the SST, the thermal radiation emitted by the sea surface can be computed by using fundamental laws of physics; From ERBE, we obtain the thermal radiation escaping to space in regions of cloudless skies; the difference between the surface emission and that escaping to space over cloudless skies is the energy trapped by the gases which is an estimate of the *atmospheric greenhouse effect, Ga. It is important to note that Ga measures the trapping by the entire atmosphere from the surface to the top of the atmosphere. These results quantified the magnitude of Ga as well as its variations. The most relevant part is that Ga increased significantly from the cold mid and high latitude oceans to the warm tropical oceans. The major source for this increase is the increase in atmospheric water vapor concentrations (since* $CO_2$ *does not vary with latitude or with SSTs)* with sea surface temperature. However, variations in Ga with SSTs are governed not only by total water vapor content of the atmosphere but also by the vertical distributions of water vapor concentrations and of temperatures from the surface to the tropopause. Thus it is very significant that, for hemispherical averaged conditions, the rate of increase of Ga with SST is nearly similar for the various seasons and, for the same season, it is also similar for the northern and southern hemisphere oceans. *Furthermore, the mean rate of rise of increase of Ga with SST is consistent with the thermodynamic theory for the coupling between temperature, water vapor concentration and its greenhouse effect.* The data also reveal the importance of dynamic processes. For example, in regions of deep convection over warm oceans such as the equatorial western Pacific ocean, the greenhouse effect reached maximum values exceeding (by about 20 percent) the value that can be ascribed to the thermodynamic coupling, while in regions of sub-tropical oceans Ga is less by about 20 percent.

**Implications to Global Warming:** The hemispherical or global rate of increase of Ga with SST as estimated from the ERBE data for the present day climate, is within 20 percent of that predicted by the climate models that yield between 2 to 4 C warming due to doubled $CO_2$. *This agreement, by itself, does not necessarily demonstrate proof or a convincing evidence for the positive amplification of the water vapor feedback in global warming.* We are a long way from establishing such a proof. However, the following two results provide a compelling evidence for the positive water vapor feedback effect. First, the mean rate of rise of Ga with SST in the model control climate is similar to that in the observed data. Second, more detailed studies with the ERBE data have shown similar rise of Ga with SST obtained by correlating monthly variations for nearly 60 months of available ERBE data.

### III. THERMOSTAT HYPOTHESIS FOR REGULATING MAXIMUM SSTS IN THE PRESENT CLIMATE

Dr. W. Collins and I published a paper on this topic in the May 1991 issue of the British journal Nature. This paper used ERBE and SST data along with other available meteorological data. It dealt primarily with the equatorial Pacific which is an important region atmospherically because it contains a large pool of very warm water with SSTs peaking between 30 C (86 F) to 31 C (the maximum temperature for the present day world oceans). This is especially true during the so-called El-Nino events (which occur once every 2 to 6 years) when the warm pool spreads from the western to the central equatorial Pacific across the date line. These warming events are well known to be a result of the natural oscillations of the coupled ocean-atmosphere system. An El-Nino event happened in 1986/87 and we used this as a natural experiment to understand how the water vapor greenhouse effect and cloud forcing responded to the ocean warming. Over just the equatorial Pacific, we found large increases in the atmospheric greenhouse effect, cloud greenhouse effect and comparable increases in the cloud reflection of solar energy. These increases are due to large increases in water vapor and thick ice clouds resulting from the effects of deep convection forming preferentially over the warmer oceans.

Our paper's central hypothesis—as yet unproved—is that a possible "super greenhouse effect" which we found to occur in regions where maximum SSTs and deep convection occur together, would be moderated by increased cloudiness resulting from deep convection. We say this because we have observed that increased ice clouds significantly reduce the solar energy incident on the equatorial ocean during the El-Nino warming. We hypothesize that, this cloud induced reduction of solar energy should limit maximum SSTs to less than 32 C (about 90 F).

*This thermostat hypothesis, even if it is proved, is valid only for the present climate and that too only for regions of maximum SSTs accompanied by deep convection.* We

are far away from proving this. A hypothesis including ours, by definition is a tentative explanation of empirical data. It is possible that alternate hypotheses can be formulated to explain our data.

**Implications to Global Warming:** *It is premature to extrapolate the thermostat hypothesis to the global warming since we have not even proved it for the present climate.* Let us consider the purely hypothetical situation that the hypothesis applies in the greenhouse rich atmosphere. Even if it is valid globally it will have minimal impact on global warming estimates since the mean temperature of the ocean is less than the maximum SST by about 10 to 15 C. *If, on the other hand it is valid regionally such as the equatorial Pacific ocean, it may only exacerbate the global warming problem.* Because, if the warmest waters do not respond but the rest of the oceans warm, the horizontal gradients in SST will be altered. There will then be significant perturbation to the circulation and weather patterns since SST gradient is one of the controlling parameters for the meteorology.

**Impact on Climate Models:** The changes in the SSTs along with the observed changes in atmospheric circulation, convection, the atmospheric greenhouse effect and cloud forcing make the El-Nino event a critical natural experiment to test and validate our model treatment of equatorial ocean-atmosphere coupling, convection and cloud-radiative interactions. These are some of the central issues of global warming. This is the fundamental message of our paper.

Senator GORE. Well, you have set a sterling example, Dr. Ramanathan. I appreciate that in more ways than one. Thank you. We will move now to Dr. Albert Arking from NASA.

## STATEMENT OF ALBERT ARKING, Ph.D., SENIOR SCIENTIST, NASA GODDARD SPACE FLIGHT CENTER, GREENBELT, MD

Dr. ARKING. Mr. Chairman, it is a pleasure for me to appear before you and comment on what I believe are some of the difficulties in trying to assess the causes of recent temperature changes and predicting the climatic consequences of increasing greenhouse gases.

We have a good understanding of many of the physical processes that govern atmospheric behavior, but some processes are quite complicated and they continue to elude us. As you mentioned in your opening remarks, Mr. Chairman, one critical problem is water, the very substance that makes life on Earth possible.

The more reliable parts of our model tell us, for example, that changing water in the upper troposphere, where there are very minute amounts, can have as much of an impact as the same percentage change in the lower troposphere, where the bulk of the atmospheric water vapor resides. Or, just shifting 10 percent of the clouds from daytime to nighttime without changing the daily mean cloud cover will have a substantially greater effect than the doubling of greenhouse gases.

So, before we can assess the impact of doubling of the greenhouse gases, we will have to find out what happens to water vapor in the upper troposphere as the Earth begins to heat up, and how the clouds will respond.

As you indicated, the direct effect of doubling $CO_2$ is relatively small, something like about 1 degree Celsius mean global average if you double the $CO_2$. And models that indicate responses as high as 5 degrees Celsius include the secondary effects associated with changes in water and other variables—what are called feedbacks.

Here is where there are wide differences amongst models. Almost all the climate models exhibit large water vapor feedback. That is, as the Earth warms up more water vapor gets into the atmosphere and, since water vapor is itself a greenhouse gas, it warms the atmosphere and the surface, so that the net effect on the climate system is much greater than if water vapor remained fixed.



My colleague, Prof. Richard Lindzen of MIT, has questioned this process, exposing a potential weak point in climate models, and he will probably address this issue.

Water in the form of clouds participates in another feedback process. Only in this case it is not Lindzen against the models, it is models against models. In a recent review of research on the radiative effects of clouds and their impact on climate, I found that there are a variety of methods that are used to represent clouds in models, leading to wide discrepancies amongst them. And one could easily account for a factor of two to three in the warming anticipated from greenhouse gases just due to the differences amongst the models in the way they treat clouds.

Clearly, to provide forecasts with enough accuracy to be useful to policymakers we need more data, we need time to analyze the data, and we need to improve and validate our models.

Unfortunately, we cannot experiment with the climate system like we do with models. But there is something that occurred several months ago, the eruption of Mount Pinatubo, which could be considered a natural experiment. Our models suggest that there will be a substantial decrease in global temperature over a short period of time of a few years or so duration—that should be detectable if our models are correct.

Looking into that possibility and seeing what happens over the next few years may give us a clue as to how we might improve our models. That, along with the data that we will continue to collect and analyze.

Thank you.

[The prepared statement of Dr. Arking follows:]

### PREPARED STATEMENT OF DR. ALBERT ARKING

It is a pleasure for me to appear before you today and comment on what I believe are some of the difficulties in trying to assess the causes of recent temperature trends and to predict the climatic consequences of increasing greenhouse gases.

The ultimate test of understanding of any object or system is the ability to describe its behavior under various conditions. So it is with climate. What will happen to the world's climate under any of a large number of possible scenarios—whether man-induced, by burning fossil fuels, or natural events, such as the eruption of Mt. Pinatubo? Are there other deterministic factors, such as variations in the output of the sun, that may be causing changes in climate, and is it possible that internally-induced changes take place that are inherently unpredictable? Unfortunately, the answers to these questions are at this time far less precise than we would like them to be.

We have a good understanding of many of the physical processes that govern atmospheric behavior. But some processes are quite complicated and they continue to elude us. While the elusive processes often appear like details in a large system where one would otherwise expect systematic behavior, it is not the case. Sometimes the "details" turn out to be critically important. The more reliable parts of our models tell us, for example, that changes in the minute amounts of water vapor in the upper troposphere can have a greater impact than comparable changes (on a percentage basis) in the lower troposphere, where the bulk of atmospheric water vapor resides. Or, just shifting 10 percent of the clouds from daytime to nighttime, without changing the daily mean cloud cover, will have a substantially greater effect than doubling of the greenhouse gases. So, before we can assess the impact of the doubling of the greenhouse gases, we will have to find out what happens to the water vapor in the upper troposphere as the earth begins to heat up, and how the clouds will respond. That is where the models are least reliable.

Water in all of its forms is the weak point in our attempts to understand climate. If somehow the water did not change—i.e., its distribution as a gas within the at-

mosphere, or as small droplets in the form of clouds, or as ice or snow on the surface, did not change as the earth warmed up in response to the greenhouse gases, the problem would be much simpler. In that case the mean temperature of the earth would increase by about 1 degree Celsius in response to a doubling of the greenhouse gases, and there is little dispute on this result. Models that indicate responses as high as 5 degree Celsius include the secondary effects associated with changes in water—what are called feedbacks. Here is where there are wide differences amongst models.

The water vapor feedback exhibited by most models goes something like this: As the atmosphere and surface warm in response to the direct effect of the increase in greenhouse gases, there is greater evaporation and greater precipitation, and the atmosphere retains more water in its gaseous form (confusingly called water vapor). Since water vapor is itself a greenhouse gas, it further warms the atmosphere and surface, so that the net effect on the climate system is much greater than if water vapor remained fixed.

Professor Richard Lindzen of MIT has questioned this process, exposing a potential weak point in climate models. He agrees that water vapor increases in the lowest levels of the atmosphere, the boundary layer, where there is a lot of mixing and interaction with the surface, but in the upper troposphere Lindzen maintains that water vapor actually decreases. In terms of water vapor amount, the increase in the boundary layer greatly exceeds the decrease in the upper troposphere, so that total water vapor indeed increases. But, according to Lindzen, the decrease in the upper troposphere, albeit the amounts are minute, is far more important as far as the greenhouse effect is concerned. A water molecule in the upper troposphere can have a greenhouse effect that is hundreds of times greater than in the lower troposphere. So the issue of water vapor feedback depends critically on whether water vapor increases or decreases in the upper troposphere as the climate system responds to the effects of $CO_2$ and other greenhouse gases.

Water, in the form of clouds, participates in another feedback process. Only in this case it is not Lindzen against the models, it is models against models. Or even with the same model, just make some changes in the way one treats clouds—as was done recently at the British Meteorological Office—and you can change cloud feedback from being large and positive (i.e., strongly reinforcing the effect of the greenhouse gases) to a negative feedback, which counteracts the greenhouse gas effect.

Clearly, we need more data, we need time to analyze the data, and we need to improve and validate our models. I see the focus of research over the next few years on the problem of how water vapor gets distributed to the upper troposphere, and how clouds change as the earth and surface warm up and circulation patterns change in response to the direct effects of the increase in greenhouse gases.

Clouds pose a particularly difficult problem because of their extreme inhomogeneity. Simple descriptions like "50 percent cloud cover at an altitude of 5 kilometers" are not enough. Even the amount of liquid water in the cloud does not necessarily convey how much sunlight the cloud will reflect, absorb, or transmit; it depends on microphysical features, such as the size of the particles, as well as macrophysical features, such as the spatial distribution of the cloud.

Satellites provide a unique vantage point from which to measure cloud properties, because a few satellites can cover the entire globe. Although radiometric sensors can be designed to provide excellent horizontal resolution, the poor vertical resolution is a limitation. Without an active system, such as a lidar, it is difficult to get information about the vertical structure of clouds, which often are multi-layered. Often one has to use indirect means—e.g., combining radiance measurements in the visible, near infrared, and thermal infrared spectrum, and applying theoretical models—in order to determine the parameters we need to measure. Up to now, satellite-based cloud data sets have been based on sensors of opportunity—i.e., sensors that were designed primarily for other purposes. Much of my own research is now focused on developing techniques for improving the retrieval of cloud parameters from space, including the design of sensors dedicated to measurement of cloud parameters.

As we develop improved techniques for measuring cloud parameters and obtain more and better information about clouds—and let me add the same holds true for atmospheric water vapor, especially the critical measurements needed in the upper troposphere—we will develop a better understanding of the physical processes involving water, as a gas and as clouds in the atmosphere, and as liquid, ice, or snow on the surface, and we will be able to improve our climate models.

I thank you for this opportunity to present a brief comment on what I believe are the main obstacles to our ability to predict the future course of the world's climate, and indicate the role that satellites might play in helping overcome those obstacles. I will be happy to answer questions.



Senator GORE. Thank you very much.

I might explain. You might have already guessed the significance of the light system. Dr. Robert Cess.

## STATEMENT OF ROBERT CESS, Ph.D., DISTINGUISHED SERVICE PROFESSOR, INSTITUTE FOR ATMOSPHERIC SCIENCES, STATE UNIVERSITY OF NEW YORK AT STONY BROOK, STONY BROOK, NY

Dr. CESS. Thank you, Mr. Chairman, and thank you for the invitation to testify at this meeting.

I also want to apologize for the brevity of my written statement. It was hastily scribbled in a hallway in Rome last week and faxed from there.

For the past several years I have been in charge of the Department of Energy-sponsored project to intercompare general circulation models. These are the numerical climate models that are used to try to understand future climatic change. And one of the things we have looked at in that intercomparison is the specific role of clouds and how clouds might either amplify or damp the initial climate forcing caused by increasing greenhouse gases.

What we find from that intercomparison is that the models disagree considerably with respect to this phenomenon of cloud feedback. Some of the models produce slightly negative cloud feedback, some near zero cloud feedback, others very strong cloud feedback.

The basic conclusion out of that study has been simply that we have to improve the treatment of clouds within the models if the models are ultimately going to be reliable climate predictors.

The second thing I have been involved with for the past several years is the Earth Radiation Budget Experiment, a NASA satellite program, the same thing that Dr. Ramanathan just mentioned a few minutes ago. And one of the exciting things we found there is the impact of clouds upon the present climate—and we have to know, to understand the present climate, before we can understand the future climate. And what we found from that is that clouds radiatively cool the present climate.

That is a conclusion that has been vastly misinterpreted by numerous people. I have seen comments in august scientific journals such as Newsweek magazine to the effect that clouds cool the present climate, therefore clouds will offset global warming. And it does not work that way.

If, for example, as the globe warms that cooling lessens, that would be a positive feedback mechanism. If as the globe warms the cooling increases, that would be a negative feedback mechanism. The problem right now is that we do not know the sign of the feedback, much less the magnitude.

Thank you.

[The prepared statement of Dr. Cess follows:]

### PREPARED STATEMENT OF PROF. ROBERT D. CESS

For the past several years I have been in charge of a DOE-sponsored project, the goal of which is to intercompare and understand radiative climate feedback mechanisms as produced by a number of general circulation models (GCMs). There are currently 18 institutions, spanning nine different countries, participating in this project. A primary conclusion to date 15 that cloud-climate interactions comprise a major uncertainty with respect to the use of GCMs as vehicles for projecting future

climate change as caused by increasing concentrations of atmospheric greenhouse gases.

Senator GORE. Thank you very much. Dr. Robert Charlson.

## STATEMENT OF ROBERT CHARLSON, Ph.D., PROFESSOR OF ATMOSPHERIC SCIENCES AND ADJUNCT PROFESSOR OF CHEMISTRY, DEPARTMENT OF ATMOSPHERIC SCIENCES, UNIVERSITY OF WASHINGTON, SEATTLE, WA

Dr. CHARLSON. Mr. Chairman, my area of study is atmospheric chemistry, with emphasis on the role of chemical processes as determinants of the physical properties of atmospheric aerosol particles. The atmospheric aerosol consists of small particles of a variety of solid and liquid substances that are suspended in the air.

Sulfate compounds often dominate the mass of the particles, as well as their physical properties and effects. These sulfate aerosol particles are produced in the atmosphere from chemically reactive sulfur-containing gases. Both natural gaseous emissions, like dimethylsulfide from phytoplankton, and pollution emissions, like sulfur dioxide, from powerplants, produce sulfate particles.

There are two main physical effects of these submicrometer sized particles. First, they reflect some sunlight toward space, thereby reducing the amount of solar energy absorbed at the Earth's surface. Second, these same particles can act as nuclei for formation of cloud droplets, and it is in this role that they are a major factor in controlling the amount of sunlight that is reflected upward by the clouds.

The former is referred to, that is the reflection of light by the aerosol particles, as the direct effect of the particles. The latter is called the indirect effect of particles on the reflectivity of clouds. The magnitude of the direct effect can be estimated with an uncertainty of roughly a factor of two. The magnitude of the indirect effect is much less certain, although the sense of both effects is to reflect sunlight away from the Earth and to cool parts of the Earth.

Our studies of the direct effect of anthropogenic sulfate aerosol indicate that it produces a loss of about 1 watt per square meter when averaged over the Northern Hemisphere. Its effect in the Southern Hemisphere is essentially zero. This aerosol loss of 1 watt per square meter is comparable in magnitude, but opposite in sign, to the current forcing by anthropogenic $CO_2$, which is about 1.5 watts per square meter.

While anthropogenic sulfate may thus appear to compensate for some greenhouse warming over the Northern Hemisphere, it is important to note that it does so only in the hemispheric average. The highly nonuniform geographical distribution of sulfate, which is caused by its short lifetime in the atmosphere, results in patches of higher reflectivity over and downwind of the industrial regions of the Northern Hemisphere.

Clearly, greenhouse gas effects and aerosol effects cannot simply cancel each other because they do not coincide at the same place and time.

I will conclude with two questions: Why did we fail to discover earlier this large climatic forcing? And are there any other aerosol-related terms still missing from the heat balance equation? Clearly,



it is my opinion that research in the United States on atmospheric aerosol has been inadequate.

Thank you for the opportunity.

[The prepared statement of Dr. Charlson follows:]

### PREPARED STATEMENT OF PROF. ROBERT CHARLSON

My name is Robert Charlson. I am a Professor of Atmospheric Sciences and of Chemistry at the University of Washington in Seattle. My area of study is atmospheric chemistry, with emphasis on the role of chemical processes as determinants of the physical properties of atmospheric aerosol particles. I and my research group have done substantial field observations, both in pristine areas and in polluted, industrial regions. We also have performed theoretical and modelling studies of the particles in the air with emphasis on rainwater composition, visual air quality and more recently, on the role of the atmospheric aerosol in regional and global climate. The latter is the topic that I will address today.

The atmospheric aerosol consists of small particles of a variety of solid and liquid substances that are suspended in the air. As one particular class of aerosol particle, sulfate compounds are often a component which dominates the mass of the particles as well as their physical properties and effects. These sulfate aerosol particles are produced in the atmosphere from chemically reactive, sulfur-containing gases. Both natural gaseous emissions (like dimethylsulfide from oceanic phytoplankton) and pollution emissions (like sulfur dioxide from burning fossil fuels and from smelting) produce sulfate particles which range in composition from sulfuric acid to ammonium sulfate.

There are two main physical effects of these submicrometer-sized particles. First, They reflect some sunlight back to space, thereby reducing the amount of solar energy absorbed at the earth's surface. Second, these same particles can act as the nuclei for formation of cloud droplets, and in this role they are a major factor controlling the amount of sunlight that is reflected upward by the clouds. The former is referred to as the direct effect of the particles because they interact directly with sunlight. The latter is called the indirect effect of particles on the reflectivity of clouds. The magnitude of the direct effect can be estimated with an uncertainty of roughly a factor of two. The magnitude of the indirect (cloud nucleating) effect is much less certain although the sense of both effects is to reflect sunlight away from the earth and to cool parts of the planet.

Our studies of the direct effect of anthropogenic sulfate aerosol indicate that it produces a loss of about one watt per square meter when averaged over the Northern Hemisphere. Its effect in the Southern Hemisphere is essentially zero. This aerosol loss of one watt per square meter is comparable in magnitude but opposite in sign to the current forcing by anthropogenic $CO_2$, which is about 1.5 watts per square meter. While anthropogenic sulfate aerosol may thus appear to compensate for some greenhouse warming over the Northern Hemisphere, it is important to note that it does so only in the hemispheric average. The highly non-uniform geographical distribution of the sulfate, which is caused by its short (few day) lifetime in the atmosphere results in patches of higher reflectivity over and downwind of the industrial regions of the Northern Hemisphere. This haze is easily recognized by travelers in commercial aircraft over the eastern U.S. One of the well-known results of this is a substantial loss of solar energy reaching the ground. The annual average loss is estimated to be around 7 percent for much of the eastern United States, or several watts per square meter. Again, I reiterate, greenhouse gas effects and aerosol effects cannot simply cancel each other because they do not coincide at the same place and time.

While the magnitudes of the greenhouse and direct aerosol forcings can be estimated and while their mechanisms are well understood, it is much more difficult to understand and predict the meteorological consequences of the geographically dependent forcing. In this context, it seems important to point out that the concern over global climate change has more to do with the geographical distribution of the weather (i.e., amounts of rainfall and sunshine, wind, storms, etc.) than it has to do with the global average temperature.

I will conclude with two questions: Why did we fail to discover earlier this large climate-related forcing and are there any other aerosol terms missing from the heat balance equation? Both of these questions can best be answered by a clear statement that research in the United States on atmospheric aerosol has been inadequate. There are several reasons for this. First, funding for such studies has emphasized applied research—cloud seeding, engineering and military objectives. This practical focus did not provide adequate support for either the fundamental science

or global-scale studies. Second, funding has fluctuated with the urgency or popularity of the application. Third, and perhaps most important, most studies of the atmospheric aerosol have been carried out within the confines of narrow academic disciplines. This resulted in a lack of coupling of the studies of the chemical processes that produce and control the amount of aerosol to the studies of the physical consequences of the aerosol. So, at the moment, it is not possible to provide quantitative estimates of the magnitude of the so-called indirect (cloud mediated) effect, nor can we know with certainty whether we have even identified all the major aerosol-related terms in the heat balance equation.We cannot even indicate whether or not feedback exists in the natural sulfur cycle, involving biogenic dimethylsulfide.

What is needed to remedy this situation is a program of research which integrates all the necessary scientific disciplines, ranging from chemistry and physics to meteorology. In order to achieve this, it appears necessary to involve four key governmental units in an integrated aerosol research program: NASA, NOAA, DOE and NSF. CEES may be an appropriate entity to assist in achieving the needed integration.

Thank you for the opportunity to make this statement.

Senator GORE. Thank you very much. Dr. Lindzen.

## STATEMENT OF RICHARD S. LINDZEN, Ph.D., ALFRED P. SLOAN PROFESSOR OF METEOROLOGY, DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCES, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MA

Dr. LINDZEN. Thank you, Mr. Chairman. Thank you for the invitation.

I will try and restrict my comments to a few things. My area of specialty is actually dynamics of the atmosphere. I was struck some years ago by the fact that, despite compelling arguments for warming, data for the past did not support the scenarios with greater than 2 degrees warming. This is not just data for the past 100 years, but, according to Rhodes Fairbridge at Columbia University, over the last 4 billion years the model results are incompatible with what we know of sea surface temperature at the equator.

So, the question was is there any way in which the models are misbehaving? And what one discovers quickly is that the greenhouse addition of carbon dioxide is so small that there are many processes whose uncertainty swamps the perturbation due to $CO_2$. Indeed, no current model of the atmosphere can predict today's temperature of the Earth without what is called "tuning."

Now, water vapor attracted my interest because of its very major role among these factors. It is not the only one, but it does account, together with layer clouds, for about 98 percent of the existing greenhouse effect. The ability to calculate water vapor determines our ability to calculate clouds in part. Vice versa, detrainment from large clouds, creation of cirrus outflow, determines our ability to calculate water vapor.

As has already been mentioned, without water vapor the response to a doubling of $CO_2$ is modest. If there are positive feedbacks it will be larger, if there are negative feedbacks it will be smaller.

In current models, the largest feedback by far is due to water vapor, and the role of other feedbacks depends on the inclusion of the water vapor feedback. If you do not include the water vapor feedback, there is no current model I know of that will produce warming due to a doubling of $CO_2$ even as large as 2 degrees Centigrade, assuming the other feedbacks, like clouds and snow ice, are positive. As we have already heard, that is in great doubt.



As Dr. Arking has mentioned, water vapor is not equally important at all levels. There is a great emphasis on importance for water vapor at high altitudes. Indeed, a molecule of water vapor at 12 kilometers is 1,000 times more important than a molecule at 2 kilometers, and molecules near the ground have almost no effect.

Yet, most of the water vapor in the atmosphere is within 2 kilometers of the ground.

Now, once we shift to upper level water vapor we have big problems. We do not monitor water vapor above 6 to 9 kilometers, at least not on a regular basis. We do not quantitatively understand the processes which determine water vapor above 2 to 3 kilometers. And in the models, due to numerical problems, which sounds very mundane, they have great difficulty dealing with a quantity like water vapor that varies by factors of 1,000 to 10,000 in density over the troposphere, which, let us say, is as low as 12 kilometers, with only 2 to 20 levels.

Indeed, many models produce negative water vapor and their water vapor distributions are largely determined by fixes to this problem.

I think it is safe to say that even water vapor problems alone render current models incapable of calculating the response to enhanced $CO_2$. The situation does not improve when one considers other uncertainties, and I believe there is simply no basis for saying the range of 1.5 to 5 degrees warming is likely.

I think the conclusion we reach is we need to understand the system better. That is no surprise. But I would emphasize that understanding, although it depends greatly on large programs of observation and supercomputers, is also an activity of the intellect.

I think the development of conceptual frameworks is extremely important. As a theoretician, it is clear my concern about such foundations is self-serving, but I believe my concern about their emphasis is also well-founded.

Finally, I would like to emphasize collecting, organizing, analyzing data from the past. This is the one most useful test we have of our models and I think the fact that no current model can simulate the cycles of glaciation over the past 2 million years does not lend confidence to our predictions for the future.

Thank you.

[The prepared statement of Dr. Lindzen follows:]

### PREPARED STATEMENT OF RICHARD S. LINDZEN

The role of water vapor in climate and climate modelling is both self-evidently crucial and confusing. Water vapor and stratiform clouds currently account for about 98 percent of the greenhouse effect. The ability of models to forecast stratiform clouds, moreover, depends crucially on the correct treatment of water vapor (Kiehl and Williamson, 1991). In present models, the largest single positive feedback is due to water vapor (referred to as the water vapor/lapse rate feedback; changes in the water vapor distribution are almost invariably associated with changes in lapse rate). Without positive feedbacks, the globally averaged equilibrium response to a doubling of $CO_2$ is from 0.6–1.2 degrees C (depending on the model). Most GCMs cluster around 1.2 degree C, but this might already be a significant overestimate. This value multiplied by the gain due to feedbacks gives the actual response.

Given the approximate algorithm for the effect of feedbacks on gain, $gain=1$ divided by $1-\Sigma f_i$, where the $f_i$'s are the feedback factors due to various processes, we see that gains due to various processes are neither additive nor multiplicative. Rather

the feedback factors are additive (see Hansen, et al., 1981, Schlesinger, 1986, and Arking, 1990 for reviews of feedbacks). For typical models, the feedback factor due to water vapor/lapse rate is about 0.4, the factor due to clouds is about 0.2, and that due to surface albedo is about 0.1. Clearly, none of the feedbacks alone produce a great deal of gain. However, if one starts with the water vapor/lapse rate factor and adds the remainder, the response can become substantial. On the other hand, *without the water vapor/lapse rate feedback, no other known feedbacks will lead to an equilibrium response as large as even 2 degrees C (assuming such feedbacks are indeed positive—a matter of considerable doubt).* For all of the above reasons, it is absolutely critical that water vapor be dealt with correctly.

The situation, however, is made extremely difficult by the fact that the effect of water vapor on surface temperature is not simply proportional to the total amount of water vapor above any point. Rather, comparable percentage changes in specific humidity at all levels in the troposphere are comparably effective in influencing surface temperature. Now, specific humidity decreases by 3-4 orders of magnitude between the ground and the tropopause. Thus, a molecule of water vapor at 12 km is about 1000 times as effective as a molecule near 2 km. Interestingly, water vapor very near the surface (where specific humidity is greatest and where the bulk of the column water vapor resides) is almost totally ineffective in altering surface temperature. Thus, the role of water vapor both as a greenhouse gas had relatedly as a feedback factor depends primarily on water vapor at upper levels. Unfortunately, in dealing with upper level water vapor we are confronted with three major difficulties: 1) We have no routine measurements of water vapor above about 6-9 km; 2) We do not know the basic physics involved in the water vapor budget at these levels; and 3) Our current numerical models are unable to numerically deal with the advection of rapidly varying (spatially and probably temporally) small quantities of water vapor. With respect to the last item, most models produce regions of negative specific humidity which are filled in by arbitrary borrowing algorithms. These "borrowing" routines commonly play a major role in model water vapor budgets. Even ignoring numerous other factors, the above 3 items alone make it virtually impossible for models today to meaningfully predict the climatic impact of increasing minor greenhouse gases. As a result, discrepancies between model predictions and historical climate behavior cannot be surprising.

Much of the above has been known for some time; however, much has also been done in the past two years to clarify matters. The state of observations is well described in NASA (1991). Papers by Rasch and Williamson (1991a,b) amply document numerical problems involved in calculating atmospheric water vapor. Lindzen (1990) explained the reasons why upper level water vapor is important to the overall greenhouse effect, and Arking (1990) has documented the fact that the minuscule amounts of water vapor in the upper troposphere are as important as the vastly greater amounts of water vapor in the lower troposphere in determining surface temperature. Arking, in fact, showed that it was entirely possible to increase the column density of water vapor while markedly reducing the net greenhouse effect. The source of upper level water vapor is still not well understood, though it is likely to be transported via cumulonimbus convection. However, the actual amount of water vapor supplied to the upper troposphere depends critically on the water and especially the ice content of the detrained cloud air and the survival of such hydrometers in the ambient air. Without detrained ice and water, detrained saturated cloud air would only maintain a very dry upper troposphere. This fact, while widely known, was emphasized by Betts (1991). Unfortunately, we do not currently know what determines such matters as the ice content of detrained air. There are also discrepancies between observations and calculations for the lifetime of detrained ice crystals (Braham and Duran, 1967). Some of these matters are discussed by Sun and Lindzen (1991) wherein it is shown that the easiest explanation of the increased lapse rates during the last major glaciation 18,000 years ago (Broecker and Denton, 1989) calls for a great increase in upper level water vapor during this period. This would imply a strong negative water vapor feedback.

The IPCC Assessment (Houghton, et al., 1990) took a more certain view of the role of water vapor than can now be maintained. In part, this was due to the assumption that near surface water vapor (which retains relatively fixed relative humidity) which dominates the water vapor column density also dominates water vapor's contribution to the greenhouse effect. It was also believed that Raval and Ramanathan (1990) had observationally demonstrated the positive water vapor feedback using satellite observations of outgoing long wave radiation. Raval and Ramanathan had defined a local greenhouse parameter which ignored the existence of lateral heat transport (i.e., transport from tropics to poles, transport from the warm maritime continent to the cooler eastern Pacific, etc.). In assessing the variation of this parameter with surface temperature, moreover, Raval and Ramanathan



assumed that lapse rate distributions were independent of surface temperature. Arking (1991b) has shown that at least half the effect that Raval and Ramanathan attribute to water vapor is obtained using fixed specific humidity and using US Standard Atmosphere temperature profiles appropriate to different surface temperatures (vis Figure 1). This is almost certainly an underestimate of the real variation of temperature profiles. Indeed, it is readily shown that deviations of temperature profiles by only a degree or two from assumed constant lapse rates wreaks havoc with the results of Raval and Ramanathan. Thus, a "certainty" which was essential to any confidence at all in model results is now known to be lacking.

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FIGURE LEGEND

FIGURE 1. The normalized greenhouse parameter, g, as defined by Raval and Ramanathan (1989). Observed values as a function of analyzed surface temperature for 2.5 degrees times 2.5 degrees regions are shown by scattered points, as is R&R's least squares linear fit through these points (solid line). Also shown is the calculated distribution of g—assuming a fixed distribution of water vapor appropriate to subarctic summer (SAS), and various standard atmosphere temperature profiles (midlatitude winter (MLW), midlatitude summer (MLS), tropics (TRO) and subarctic summer (SAS)). This is shown by a dashed line which was calculated by Arking (1991b). The temperature effect accounts for half of R&R's slope. Much of the remaining slope is due to the omitted effect of equator to pole heat flux.

Infrared opacity is greatest at the ground over the tropics, and diminishes as one goes poleward and upward. Air currents bodily carry heat to regions of diminished infrared opacity where the heat is radiated to space -- balancing absorbed sunlight.

Lighter shading schematically represents reduced opacity due to diminishing water vapor density.

FIGURE 1.—Clear-sky greenhouse effect normalized by infrared emission ($g$) as a function of surface temperature, April 1985. Values are monthly averages for each 2.5 degree times 2.5 degree region. The solid line indicates a least-squares fit through all the points. Fits done individually through Northern and Southern Hemisphere points do not deviate by more than 3 percent.

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STATEMENT ON GLOBAL CHANGE

Global warming is almost certainly inevitable—regardless of man's presence on earth. So is global cooling. The Earth's climate has been both warmer and colder than it is at present (mostly warmer); climate is always changing and there is virtually no chance that we will alter this state of affairs. However, the quantitative expectation of substantial global warming (more than 1 degree C or so) arising in the next century because of man's production of minor greenhouse gases ($CO_2$, CFC's, methane, etc.) is without substantive scientific foundation. It is worth noting that the major greenhouse substance is water in the form of water vapor and layer clouds—which accounts for over 98 percent of the current greenhouse effect. It is sometimes noted that many minor greenhouse gases are directly related to man's activities, whereas water vapor and layer clouds are internally established by the atmosphere. However, it is obvious that models that do not properly deal with the major greenhouse substances will be inadequate for evaluating the response to minor greenhouse gases. As concerns catastrophic predictions (5 degree C warming), it should be emphasized that we are not dealing with plausible consequences of a well established understanding, but rather with the consequences of identifiable model errors. Such consequences are, moreover, inconsistent with the history of the Earth's climate to date.

As concerns past climate, it is noted in the IPCC Scientific Assessment (Houghton, et al., 1990) that the observed warming over the past century (during which time we have increased minor greenhouse gases by about 50 percent) is most consistent with an increase in temperature, for a doubling of such gases, of about 1.2 degree C (page 246). This estimate includes the delaying effect of the oceans and assumes that all observed warming over the past century (0.450 degree C plus-or-minus 0.15 degree C) is due to increasing greenhouse gases. However as the IPCC Assessment notes (p. 254), "it is not possible to attribute all, or even a large part, of the observed global-mean warming to the enhanced greenhouse effect on the basis of the observational data currently available." The reason for this inability is simply that the global mean temperature naturally fluctuates by this amount over periods as short as 5 years.



It has been noted that the upper limit of the IPCC range of warming predictions for the end of the next century (5 degrees C) would leave the Earth warmer than it has been at any time in human history. This assertion is, in fact, modest. According to the distinguished paleoclimatologist, Rhodes Fairbridge of Columbia University and GISS, the average temperature of the Earth has been in the range 18 degrees C plus-or-minus 5 degrees C for about 4 billion years—during much of which time the atmosphere contained many times the $CO_2$ projected for the next several centuries (Fairbridge, 1991). The model predictions exceed this range. Fairbridge also notes that equatorial sea surface temperatures have been in the range 30 degrees C plus-or-minus 1 degree C during this period. Virtually all models predicting large global warming predict 2-4 degrees C warming at the equator. Under any normal circumstances, one would conclude that the models are misbehaving—even allowing for some uncertainty in the data.

Beyond the prima facie evidence that model predictions are inconsistent with observations (and the inconsistency far transcends the above examples), are there other reasons for questioning model behavior? Indeed, there are many reasons; everyone has their favorite, and each is enough to swamp the effect of increasing $CO_2$ (recall that $CO_2$ contributes only about 1 percent to the greenhouse effect and model errors are far larger than this). Indeed, no current model can predict the mean temperature of today's Earth without what is euphemistically called "tuning".

One issue I have been focussing on in the past few years has been the role of water vapor. This issue is summarized in the accompanying statement prepared at the invitation of the IPCC in connection with the preparation of an update to their 1990 document. (It is worth noting that the preparation of an update so soon after the original publication is indicative that the original document was hardly canonical.) The main points in the accompanying document are:

1. Water vapor and layer clouds account for over 98 percent of the greenhouse effect.
2. The ability of models to predict layer clouds depends on the ability of models to predict water vapor.
3. In the absence of positive feedbacks, the equilibrium response to a doubling of $CO_2$ is in the range 0.6 degree C to 1.2 degrees C. Larger responses require positive feedbacks. Negative feedbacks will, of course, reduce the response.
4. The largest positive feedback by far in current models is due to water vapor.
5. Without the positive water vapor feedback, no model would obtain an equilibrium warming due to doubling $CO_2$ as large as even 2 degrees C (assuming other feedbacks are positive—a matter of great doubt).
6. Water vapor is not equally important at all levels in the atmosphere. A molecule of water vapor at 12 km altitude is about 1000 times more important than a molecule at 2 km in its contribution to the greenhouse effect. The effect of molecules near the surface is almost nil. Thus, although most of the atmosphere's water vapor resides in the bottom 2 km of the atmosphere, it is the water that resides elsewhere that is crucial to the Earth's climate response.[1]
7. Water vapor is not monitored above 6-9 km.
8. We do not understand the physical processes which determine water vapor above 2-3 km.
9. Due to numerical problems, models cannot currently deal with a substance like water vapor which varies so rapidly with altitude (it varies by 3-4 orders of magnitude between the ground and the tropopause). Current models commonly produce regions of negative water vapor, and the arbitrary "fixes" introduced to eliminate such impossibilities frequently play a major role in determining model water vapor.
10. It has been asserted that the observational analysis of Raval and Ramanathan (1989) proved that the water vapor feedback is positive.[2] That result is significantly due to a faulty assumption in their analysis—namely, that the shape of temperature profiles are independent of surface temperature. The interpretation

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[1] The reason for this is that, counter to the popular picture of the greenhouse, the Earth's surface does not cool primarily by infrared emission. Rather, heat (in various forms) is bodily carried from the surface by air currents to regions of much reduced greenhouse potential (at higher altitudes and latitudes), and from these regions, the heat is radiated to space. Thus, it is greenhouse gas concentrations in those regions of the atmosphere where motions deposit heat that are most important in determining the surface temperature. (The situation is schematically illustrated in the accompanying figure.) It follows that models that do not accurately depict transports by air currents, cannot accurately predict the temperature of the Earth. Current models do, in fact, have severe problems with transport.

[2] A recent study by Sun and myself suggests, on the basis of paleoclimatic data from the last major glaciation, that the water vapor feedback may, in fact, be strongly negative.

of their results is also confused by the absence of consideration of lateral heat transport.

In view of the above alone, it is clear that models are presently incapable of calculating the response to enhanced $CO_2$. The situation hardly improves when we consider the uncertainties in clouds barely touched in the above discussion), the uncertainties in ocean transport, and even the uncertainties in the behavior of $CO_2$ itself. There is simply no basis for saying that the range 1.5 degrees C-5.0 degrees C is "likely"—especially since all these values are excessive according to the behavior of the climate over the past century.

Where then does this leave us. At the least, it leaves us with a self-evident need to understand our climate, and, more generally, our environment. It seems entirely reasonable for wealthy, scientifically and technologically advanced societies to set themselves the goal of understanding the physical environment they reside in. Such an understanding would be among the greatest gifts we could leave to our successors on this planet. Such an understanding would not only enable us to anticipate currently unexpected dangers, but would also help us avoid being exploited by dangerous hysteria based on ignorance. In emphasizing understanding, I must point out that although understanding benefits from large observational programs and supercomputers, it is primarily an activity of the intellect. The development of a sound conceptual framework is essential to the planning and evaluation of large programs. Such development is monetarily cheap but difficult, and large programs can tend to deemphasize such theoretical efforts—not only because they are cheap but also because it would be embarrassing to admit that the conceptual foundations for large efforts might sometimes be absent. As a theoretician, it is clear that my concern about conceptual foundations is self-serving; I believe the concern is also well founded.

Turning more specifically to the problem of global climate change, we must certainly develop an adequate understanding of the behavior of water vapor in the atmosphere. Monitoring must be extended to the upper troposphere. Much work needs to be done to improve our understanding of the microphysics of deep convective clouds in order to know how these clouds determine the balance between the water and ice they pump into the environment and the precipitation that falls to the surface.

Of course, understanding water vapor is not the whole story. Nor are all aspects of water vapor equally important to the prediction of climate sensitivity. We need to determine what role the oceans may play in transporting heat and material. We also need to understand what determines the transport of heat, momentum, and material by the large scale circulation of the atmosphere. We are still in a position where we do not quantitatively know what determines the equator to pole temperature difference. Yet, over the history of the Earth, climate variations have been far more associated with changes in the equator to pole temperature difference than with changes in the global average temperature. Improved data for both the atmosphere and the ocean is certainly essential. However, observations must be based on well determined needs rather than available instruments and platforms. The mundane issue of the numerical and computational methodology for evaluating the equations for climate is basic. The behavior of $CO_2$ remains rich in puzzles. It is essential that we understand the sources and sinks of $CO_2$ over land and sea, and that we understand why $CO_2$ has varied in the past without human intervention. Indeed, although we cannot obtain data for the future, the past, in varying degrees, is accessible. Every effort should be made to collect, assemble, analyze and organize data for the past so as to be able to reconstruct as accurately as possible the climate of the last decade, the last century, the last millennium, the last million years, and even the last several billion years. Such reconstructions will provide the best opportunity for us to test our understanding of climate. The fact that no current model can simulate the cycles of glaciation over the past 2 million years (which we currently believe, on the basis of observations, to be forced by the Earth's orbital variations) hardly lends confidence to our predictions for the future.

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Senator GORE. Thank you. Dr. William Rossow.

**STATEMENT OF WILLIAM B. ROSSOW, Ph.D., PHYSICAL SCIENTIST, NASA GODDARD INSTITUTE OF SPACE STUDIES, NEW YORK, NY**

Mr. ROSSOW. Thank you, Mr. Chairman. Thank you for the invitation to participate in this discussion.

My advanced written testimony is even briefer than Dr. Cess'. It does not exist. I was out of the country until just recently.

So, let me just spend a few minutes saying what the basis is for comments I will be making. I am head of the Global Processing Center for the International Satellite Cloud Climatology Project, which is part of the World Climatology Research Program. This is a multisatellite data collection and analysis effort which, when you combine that data with data from ERBE and other radiation budget experiments and other field programs, constitutes a really new set of data that we can use to try to analyze the problem of cloud effects on climate.

Despite the fact that some of these programs have been going on for several years, analysis is just now beginning. This is true because you usually spend a fair amount of time just trying to make sure you have done your basic analysis chores correctly. But now we have enough data that we can really begin to look at the problems by combining various data sets.

So, I want to stress two things. One is that the data analysis has really just begun and that a comparison of these data to the models has really just begun. But these data sets give us an unprecedented, more detailed look at what the clouds are doing and so it is my belief that in the next few years we will actually resolve some of the problems that we are going to be discussing today. We will at least resolve them in terms of short-term behavior, both for

er and possibly for climate transients like the Pinatubo volcano or an El Nino.

However, I think that one of the things that happens in scientific analysis is that the question you actually think is the most important question changes as you begin to look at the answers. This is my second point that I also believe that as we do resolve some of the problems we have, we will also change our minds as to what the next problems really are.

I think the next few years will be very exciting because we will be able to ask those next questions and define the observations that we will need next.

Thank you.

Senator GORE. I am sure everybody here anticipates the results of your present research. Dr. Kevin Trenberth from NCAR.

**STATEMENT OF KEVIN TRENBERTH, Ph.D., HEAD OF CLIMATE ANALYSIS, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, BOULDER, CO**

Dr. TRENBERTH. Thank you, Mr. Chairman. I also welcome the opportunity to participate in this meeting.

In the Climate Analysis Section at NCAR, we are especially concerned with global data sets, and in my written testimony I have provided a summary of water vapor observations, and a brief summary is that the tropospheric water vapor measurements are reasonably well known, the averages at least, but we do not do a good job in determining the daily and monthly evolution of the global scale fields.

The second point I would like to make is that I am involved in a climate modeling effort at NCAR and our latest version of the model does provide, I think, convincing support for the role of convective clouds in moistening the mid- and upper troposphere. We cannot simulate today's climate unless we include that particular process.

On the role of clouds in climate, I am very concerned that the atmospheric dynamics be factored in. There has been much focus on what is referred to as cloud-radiative forcing, the radiative processes, but I am very concerned with questions like Where does the water vapor come from to form the clouds, Why do the clouds occur where they do, What form do they take, and also in forming precipitation within clouds the latent heat is released and that heat has to go somewhere?

What this says to me is that, firstly, if you look at satellite pictures and so on, the atmospheric dynamics, the winds, are very important in determining the patterns of clouds. But second, the radiative heating and also the latent heat that goes on in clouds is very important in feeding back to change the atmospheric motions. So it is an interactive system.

There has been much debate recently concerning the Ramanathan-Collins hypothesis on the thermostat mechanism in controlling sea surface temperatures, and I have been involved in that debate. I think the evidence indicates that there are other effects which are also important.

The linkages between clouds, atmospheric dynamics, and sea surface temperature, however, indicate the complexity of the overall



system and I think these must be addressed in large programs, large observational programs, that consider not only radiation but also the full climate system, the atmospheric dynamics, and climate modeling.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Trenberth follows:]

PREPARED STATEMENT OF DR. KEVIN E. TRENBERTH

My name is Kevin Trenberth. I am the Head of the Climate Analysis Section and Deputy Director of the Climate and Global Dynamics Division at NCAR, the National Center for Atmospheric Research. In my work, I am especially interested in global-scale climate dynamics; the observations, processes and modeling of climate changes from monthly to interannual to decadal time scales. I am from New Zealand and I believe that I have unique experience and expertise on the Southern Hemisphere and global atmospheric circulation. I was one of the instigators of the International Tropical Oceans Global Atmosphere (TOGA) programme (under the World Climate Research Programme) and I have served in the U.S. and still serve internationally on TOGA advisory panels. I have served on many National Academy of Science committees, panels and/or boards, and I serve on the NOAA Climate and Global Change Advisory Panel. I have been involved in the global warming debate and the Intergovernmental Panel on Climate Change (IPCC) scientific assessment activity.

With regard to the subject of clouds, I will first summarize the state of knowledge concerning basic water vapor observations in the atmosphere and briefly comment on the relevance of these observations to simulating climate with general circulation models. Water vapor is the most important greenhouse gas in the atmosphere. It is fairly transparent to solar radiation but modulates the outgoing longwave radiation (OLR). Good measurements of water vapor exist throughout the troposphere, but not with global coverage. The climate models indicate that convective clouds play a vital role in moistening the upper troposphere.

A debate has developed over the Ramanathan-Collins (1991) hypothesis concerning the role of clouds as a thermostat on the climate system. They suggested that in the region of high sea surface temperatures, deep convection develops that produce clouds which block out the sun and thus limits further sea surface warming. However, there are examples where this does not work, and the mechanism should not be applied locally because there are nearby regions of compensating effects. The hypothesis does not have general applicability and there are other known Limiting mechanisms.

A focus of the impacts of clouds on climate has been their radiative effects, but I am concerned that the role of atmospheric flow in determining patterns of clouds should not be overlooked. Recently, a very useful construct called "cloud forcing" has been introduced. It deals with the radiative effects of clouds, and so can be divided into shortwave (solar) cloud forcing and longwave (infrared) cloud forcing. However, it often tends to ignore other aspects of clouds, such as where the moisture comes from to form the clouds, why clouds occur where they do, why they have the form that they take, and the fact that in forming precipitation latent heat is realized in the clouds, thereby heating the atmosphere. All these factors mean that the atmospheric dynamics are critical in forming patterns of clouds. At the same time the atmospheric flow is strongly affected by the radiative cloud forcing and the latent heating. As a result, there is a strong coupling between clouds, the atmospheric dynamics, and the underlying surface of the ocean or land that can only be properly approached by studies that address these interactions. For example, TOGA is concerned with tropical ocean-atmosphere coupling. Interannual variations in the climate system, which are also a subject of central interest to TOGA, have been used as an indication of what may happen in longer-term climate change. However, clouds have not been a principle concern in the El Nino studies because they are of secondary importance in that phenomenon. This may not be the case in global change.

ATMOSPHERIC WATER VAPOR: WHAT DO WE KNOW

The main measurements of atmospheric water vapor are from radiosondes, which consist of a package of instruments flown through the atmosphere on a balloon twice daily at many hundreds of stations all around the world. The package is expendable, so the instrumentation is as cheap as possible. Over the years, the radiosonde itself has evolved, different countries use different instruments with differing accuracy

and precision. For water vapor, the sensor measures relative humidity (RH) and has changed with time. Special problems occur at low humidity measurements and these continue unnecessarily. In the U.S. a lithium chloride element was introduced in 1943 but was incapable of making any measurements for relative humidities less than 200 percent. About 1965, a new carbon element was gradually introduced to measure humidity. In 1973 the housing of the radiosonde was changed and this affects the radiative and ventilation characteristics of the instrument, thereby changing the readings. Recently, in 1989, a second manufacturer was added in the U.S. that currently supplies about 20 western U.S. stations. However, problems with the new instrument continue. For example, the black paint used in the air intake to the instrument turned out to be hygroscopic (water attracting) and comparisons between radiosondes from the two manufacturers reveal differences.

There are some problems with the instrument. There is a time lag response in both temperature and relative humidity measurements. There is some hysteresis in the moisture sensor (it remembers moisture), creating differences In readings of up to about 3 percent. There have long been errors in the treatment of RH for values <20 percent, a heritage of the early sensor. In the U.S. this is coded as "30" dew point depression, which the National Meteorological Center (NMC) interprets as 15 percent RH, while the National Climate Data Center uses 19 percent. Neither is correct. The actual sensor works fine but simply has not had a calibration curve supplied. Overseas, fairly widespread use is now made of a Vaisala radiosonde instrument that measures low humidities.

Aside from the low humidity problems, the accuracy of the humidity sensor on the U.S. radiosonde is 4 to 7 percent RH (high end because of hysteresis effects). With uncertainties in other instruments and balloon location drift, the net uncertainty (assigned by the European Centre for Medium Range Weather Forecasts (ECMWF)) is: 10 percent from 1000 to 500 mb (lower troposphere) and 20 percent from 500 to 300 mb (upper troposphere).

What area of the globe is one measurement representative of? One fundamental problem in using the measurements is that water vapor is not well mixed in the atmosphere, so that there are large spatial gradients (e.g. clouds, fronts), and there are rapid changes in time. The representativeness of one measurement is difficult to assess. ECMWF uses an influence radius of 250 km at 1000 mb and 300 km in upper troposphere (Illari, 1989). Thus there are too few radiosonde measurements to determine global fields.

Another form of measurement of water vapor is from satellite sensing in the infrared and microwave. These measurements have the advantage of global coverage, but at present give poor vertical resolution. Also, the retrieval algorithms make assumptions, and there are several different algorithms. The microwave results are sensitive to surface emissivity, so that the method can only be applied over the ocean and the algorithms must remove the influence of surface wind. Comparisons between radiosonde and infrared (TOVS, the TIROS Operational Vertical Sounder) retrieval measurements indicate errors of 15 percent in tropics, and 35 percent in mid latitudes (biggest errors where RH is small) (Illari, 1989). Recently, new measurements have been reported from the SAGE II instrument of RH from 6 to 12 km altitude at 1 km vertical resolution are accurate to 10 percent (Rind et al., 1991).

Given the basic data, how do we get global fields of relative humidity analyses? The method used is through a process called four-dimensional data assimilation at major centers like NMC and ECMWF. The analyses are univariate for RH, which means RH is analyzed by itself as a combination of measurements and information from the numerical weather prediction model used to provide a "first guess" as to what the field looks like. This first guess is actually a forecast from the previous analysis and is subject to errors of perhaps 20 percent. Global RH analyses have not compared well with observations (Illari, 1989) and have changed erratically with time as the numerical weather prediction model used in the data assimilation has changed, see Fig. 1 (Trenberth and Olson, 1988). Use has been made of satellite data in recent years. However, because of low humidities in the upper troposphere there is no RH analysis above 300 mb at ECMWF.

In summary, reasonably good RH information is available from radiosondes, although information in the upper troposphere is mostly confined to local or special measurements. Mean values are better known than daily and monthly time series, and the evolution of global fields is not well enough known for climate purposes.

Climate models have not been able to simulate observed moisture levels in the mid to upper troposphere without including effects of vertical transport of moisture by convective clouds. Specifically, in developing the Community Climate Model at NCAR, my colleagues have found it necessary to include a convective parameterization that detrains moisture into the upper troposphere. Any model convection scheme that "rains out" all the moisture in these clouds and which does not



detrain a fraction fails to come close to reproducing observed moisture concentrations (Fig. 2). The vertical moisture transport by convection is vital in forming the observed tropical moisture concentrations in the atmosphere which, in turn, has a strong greenhouse effect.

## THE DYNAMICS OF CLOUD FORCING

The cloud radiative forcing method for analyzing the effects of clouds on the earth's radiation budget was developed by Charlock and Ramanathan (1985). It contrasts the radiation composites for clear sky conditions with the total observed, and the difference is a direct measure of the effects of clouds on the radiation balance of the earth. In this section, it is emphasized that these are not the only effects of clouds and that there are several issues linked to cloud forcing.

First, the tropical convective regions where optically thick upper level clouds occur require a supply of moisture, since precipitation exceeds evaporation in these regions.

Second, the latent heating from precipitation in the convective regions requires upward motion and an export of heat in the atmosphere. This heating helps drives large-scale over turning in the atmosphere.

Because atmospheric mass is conserved, the rising motion in the convective regions must be balanced by sinking motion elsewhere. This can be seen by the divergent flow in the upper troposphere which changes with season (Fig. 3). The dominant patterns in Fig. 3 constitute what is known as the Hadley (north-south) and Walker (east-west) cells of large-scale overturning. In practice, the compensating sinking motion occurs over fairly warm water in the tropics and subtropics.

The large-scale subsidence creates a strongly stable atmosphere which suppresses cloud development and the vertical transport of free-atmosphere water vapor, and produces the dry zones in the tropics, some of which have high sea surface temperature. This is where the top-of-the-atmosphere outgoing longwave radiation is largest and the absorbed solar radiation at the surface is increased.

In view of the above, it is clear that an increase in shortwave cloud forcing and greenhouse effect, due to increased water vapor, in one location in the tropics necessarily means a compensating decrease in these factors someplace else in the tropics. While it appears that cloud forcing has one effect in convective areas, it has the opposite effect nearby and the two regions are closely coupled through the atmospheric dynamics. Therefore the net cloud forcing should not be considered locally, but should be averaged over the regions coupled through the dynamics (Hartmann and Michelsen, 1991).

## SEA SURFACE TEMPERATURE (SST) CONTROLS IN THE TROPICS

Ramanathan and Collins (1991) proposed that optically thick clouds in the tropics act as a thermostat in controlling high SST (above about 310C). They hypothesize that in high SST regions, deep convection develops and creates such clouds that block out the sun ("shortwave cloud forcing") and thus limit further sea surface warming.

*Discussion*

Several points relevant to this mechanism and its possible general applicability need to be made:

1) Locations of convective cloud do not depend solely on SST but also on SST gradients, and on land heating (land-sea contrasts and monsoons) from more remote regions, as well as on atmospheric dynamics (Trenberth, 1991). Consequently, spatial patterns of cloud do not closely follow those of SST, see for example see Fig. 4, for March, April, May (MAM) 198?, from Hartmann and Michelsen, 1991).

Over the Indian Ocean, where the influence of the Asian landmass cannot be ignored, regions of high SST (in MAM 1987 the highest, of over 31 degrees C, Fig. 4) occur but often with subsiding air aloft, so that the atmosphere becomes stable and suppresses convection.

Because regions of upward motion must be balanced by regions of downward motion in the atmosphere, cloud and convection cannot occur everywhere (even if SST is high everywhere). Convection is organized by atmospheric dynamics into "convergence zones" (see Fig. 5) and monsoons; (cf. the Hadley and Walker Circulations, Fig. 3). The upward motions are concentrated into small regions where there are collections of convective clouds, whereas the subsiding motions are more gradual and widespread.

Because of the atmospheric dynamics involved in generating cloud from deep convection (moisture supply, export of heat, conservation of mass) an increase in short-

wave cloud forcing in one area must be compensated by a decrease somewhere else, and radiative cloud forcing is inherently not a local problem, as noted above.

2) Ramanathan and Collins (1991) did not fully discuss the role of evaporation, and thus surface latent heat loss, as a further controlling mechanism. In general this appears to be the dominant controlling mechanism for SST in the tropics, with increases in latent heat loss from the surface of the difference of 10 W $m^{-2}$per degree C change in SST. In the tropics, this partly arises simply from the fact that warmer air can hold much more water vapor (the Clausius-Clapeyron equation). But, in addition, in regions of convection, gusty winds and cooler drier downdrafts can greatly enhance surface evaporation to twice this value (Moncrieff, 1990). Typical surface heat losses from evaporation in warm pool regions are 100 to 150 W $m^{-2}$.

3) Surface thermal radiation toward space also contributes significantly to controlling SST (higher SST, higher radiation) with a heat loss of the difference of 6 W $m^{-2}$ per degree C increase in SST in the tropical warm pools. Typical surface thermal radiative heat losses in warm pool regions are 60 W $m^{-2}$.

4) In general, when there are changes in SST, as in an El Nino event, there are strong compensations between changes in shortwave cloud (Fig. 6) and longwave cloud plus water vapor (greenhouse) effects. The increased cloudiness blocks the sun, but is more than compensated for by the increased greenhouse effect of increased water vapor plus the trapping of heat by the clouds. In regions of higher SST convective cloud typically increases, but in nearby regions there are decreases in convective cloud, so that opposite effects take place. The sum of the changes in the two radiation components (short- and longwave) with changes in SST indicates heat increases of the difference of 6 W $m^{-2}$ per degree C change in SST which virtually offsets the surface thermal radiation effects (in 3), so that the change in net radiation terms in the tropics sums close to zero. This is very robust over many areas in which there are increases and/or decreases in cloud (Hartmann and Michelsen, 1991).

5) It is likely, however, that the distribution in the vertical atmospheric column of the long- and shortwave radiative heating is different. Changes in solar radiation are more apt to be felt at the surface, whereas the longwave heating is distributed throughout the atmosphere. Therefore changes in cloudiness should have a direct effect on heating at the surface. Over the ocean, this can impact SSTs, as suggested by Ramanathan and Collins, but the effect is complicated by changes in the ocean currents and upwelling induced by changes in the atmospheric winds.

6) There is no good reason for a "magic" number such as 31 degrees C for SST maxima, and higher SSTs could occur under global warming. There are good reasons why SSTs and air temperatures are fairly uniform over large areas of the tropics and the upper limit should be fairly well defined (Wallace, 1991). Wallace argues that the distribution of SSTs in the tropics should be skewed to an absence of hot spots (i.e. large warm pools should form) because of the uniformity of atmospheric temperatures in the troposphere and rapid equilibration between atmosphere and ocean. The atmospheric temperatures are relatively uniform in the tropics because even small pressure (or temperature) gradients set up strong winds that usually quickly remove inhomogeneities.

## SUMMARY

Cloud forcing in the atmosphere is inherently a nonlocal process. There is a strong interplay between the atmospheric dynamics, cloud and with the surface of the earth or underlying ocean. Questions such as why atmospheric convergence zones and associated cloud occur where they do are inherently questions of the coupled atmosphere-ocean system that must be addressed in programs such as TOGA and Global Change.

Ramanathan and Collins (1991) proposed an effective mechanism for regulating increases in SSTs in the tropics, but other limiting factors appear to be more important. Many of the factors contributing to the balance of SST are somewhat uncertain, especially in the very warm pool regions of the globe. The TOGA COARE[1] Program is designed to address them as best they can with the resources available through a major international field program to take place from November 1992 to February 1993 in the tropical west Pacific. It is very important that adequate funding should be allocated to the U.S. research component of this international programme.

[1] COARE is the Coupled Ocean-Atmosphere Response Experiment.



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FIGURE 1.—Latitude-time series for several quantities from the ECMWF WMO archive. Shown are departures from the mean annual cycle from May 1985 to May 1989 of the relative humidity at 850 and 700 mb, in percent. Most changes seen here are spurious and associated with changes in the data assimilation system.

FIGURE 2.—The vertical profile of specific humidity at the location of Truk island (7.5 degrees N 151 degrees E) in the tropical west Pacific. The horizontal bars show the range (as given by plus and minus one standard deviation) of monthly mean observations from radiosondes at the island for the month of July. Note the horizontal scale is logarithmic and water vapor amounts (in grams of water vapor per gram of air) decrease rapidly with height. The solid profile is the result for the monthly mean from a simulation with the NCAR CCM2 climate model in which a mass flux convection scheme is included which features an overshoot of clouds and detrainment of moisture into the troposphere at cloud top. The dashed profile is the model simulated result when all the condensation in clouds is forced to precipitate out. The result in the latter case is a deficit of moisture in the troposphere compared with observations, which leads to temperatures that are too cold because of the reduced greenhouse effect. (Courtesy J. Hack, NCAR).

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FIGURE 3.—Seasonal mean velocity potential and the divergent component of the wind vectors at 200 mb for (a) December-February 1985-86, and (b) June-August 1986. The vector plotted at lower right depicts 10 $m^{-1}$. From Trenberth (1991). The arrows depict the upper tropospheric flow from regions of intense upward motion in convective areas to regions of more gradual downward motion.

FIGURE 4.—(a) Sea surface temperature (degrees C) and (b) shortwave cloud forcing (W $m^{-2}$) for March-May 1987 mapped on a Hammer equal area projection. The originals are in color and the SST map colors were chosen to emphasize the tropics. From Hartmann and Michelsen (1991).

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Mercator Satellite Relative Cloud Cover, 1400 Local, 40°N to 40°S, Mean Octas, October 1967-1970.

FIGURE 5.—(a) Mercator satellite picture of cloud cover 40 dgrees N to 40 degrees S for October 1967 to 1970; and (b) pictorial representation of the key features in (a) showing the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ), with the annual mean sea level pressure field superposed along with schematic surface wind streamlines.

FIGURE 6.—(a) Sea surface temperature (degrees C) and (b) shortwave cloud forcing (W $m^{-2}$) differences between March-May 1987-1985 mapped on a Hammer equal area projection. The originals are in color. From Hartmann and Michelsen (1991).

Senator GORE. Thank you very much.

I hope that one of the things we will come back to in the discussion to follow will be the effects that you have talked about in critiquing Dr. Ramanathan's latest study. Dr. Betts.

## STATEMENT OF ALAN K. BETTS, Ph.D., METEOROLOGIST, MIDDLEBURY, VT

Dr. BETTS. Thank you, Mr. Chairman.

As you can tell from my accent, I was educated in England, and I came to this country in 1970 and worked in the 1970's primarily on tropical weather experiments over land and over the oceans.

Since that time my work has been involved with primarily the processes of convection and clouds in the atmosphere, in all stages, from the analysis of experimental data, the development of conceptual models, and the incorporation of those models in the global forecast and climate models.

It does not really need to be said here that the atmospheric system, the climate system, is exceedingly complex, involving not only the atmosphere but the oceans and the biosphere. I agree with earlier speakers that our models are only as good as the conceptual components of which they are made.

What I want to talk about in the next 1 or 2 minutes is the water vapor feedback part of the problem, which has been correctly referred to by Richard Lindzen as one of the most important parts of the problem.

Generally, water vapor increases in the atmosphere because of its tight coupling to the temperature structure. The issue that is the major one, on which we have a limited amount of observational material and where our models still have problems, is the question of whether water vapor will increase or decrease in the upper troposphere, if there is a climate warming. The issue is particularly important in the tropics because the tropics are the warm temperature regions, where most of the evaporation and transports of water from the ocean surface take place.

It has been argued by Professor Lindzen that the injection of saturated air, saturated over ice in the upper troposphere, may dry the upper troposphere because, if there is a climate warming; that is, a warming of the ocean surface temperature, the deep thunderstorm clouds in the tropics will go to higher levels.

I have argued that this ignores the fact that most of the water input into the upper atmosphere comes in the form of ice, the ice anvils that you can see on the satellite pictures.

The other aspect of this problem is a conceptual understanding of the water vapor balance in the atmosphere; what controls the relative humidity of the atmosphere. I would argue that the evidence that we do have shows that it is controlled by radiative processes, which we do understand; and our expectation is that the relative humidity in the upper troposphere would, if anything, increase slightly, and certainly not decrease to a major extent in the event of a global warming of the tropics.

Now, I certainly agree that our observational basis is very limited. I am involved a lot in the development of improved parameterizations of clouds in global models and I am very aware of the weaknesses of those at the moment. But my assessment is that on balance the evidence is that the relative humidity of the atmosphere in the upper troposphere would not change greatly in the event of global warming, which means that the water vapor feedback is likely to be a dominant process.

I believe we should take the issue of global climate change seriously, not because we ourselves may be unable to adapt, but because the natural ecosystems may not be able to adapt to climate changes in the next 50 or 100 years, which are beyond those which they have faced in the past.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Betts follows:]



## Prepared Statement of Alan K. Betts

### 1. BACKGROUND

I was born and educated in England, with a BA (and MA) in Natural Sciences (Theoretical Physics) from the University of Cambridge in 1967, and a PhD in Meteorology from Imperial College, of the University of London, in 1970. I came to the Department of Atmospheric Science at Colorado State University in 1970 to work on the analysis of a tropical field experiment in Venezuela (VIMHEX: the Venezuelan International Meteorological and Hydrological Experiment), in which I had participated in 1969. I remained on the academic faculty at CSU until 1978, when I moved to Vermont to continue my research work independently. For the past 13 years, I have lived and worked in Vermont, supported by direct grants and contracts from the National Science Foundation and the National Aeronautics and Space Administration.

My research has dealt with atmospheric convection and clouds; their description by observations and theory, and the representation of their energy and water transports in global models, both numerical weather prediction and climate models. In the 1970s my research concentrated on convection in the tropics, and I helped plan and execute the Global Atmospheric Research Program Atlantic Tropical Experiment in 1974 (GATE) (Betts, 1974, Houze and Betts, 1978), as well as a second VIMHEX Experiment in 1972. For this research, I was awarded the Richardson Prize of the Royal Meteorological Society in 1974, the Meisinger Award in 1977 and a Special Award in 1978 by the American Meteorological Society. I coordinated the convection research for GATE for the National Academy of Science panel. In the past decade my research has broadened to cover as well the analysis of clouds and convective boundary layer processes over land and the oceans, both in the tropics and mid-latitudes, and the representation of convective processes in global models. I am currently a member of the National Academy panel for the International Satellite Cloud Climatology Project.

### 2. WATER VAPOUR AND THE CLIMATE SYSTEM

The earth's climate system, which involves not only the atmosphere, but the ocean circulations and the biosphere, is exceedingly complex. As a result of theoretical studies, a global observing system, and the development of computers fast enough to model the global atmosphere at sufficiently high resolution, we have made remarkable progress in our understanding in the past 20 years. Yet our present models are still extremely simple, when compared with the complexity of the real climate system of the earth. As a result our global climate models are only as good as the conceptual components of which they are made.

I wish to discuss the links in the chain between the known global increase of the gases such as $CO_2$, $CH_4$ and the CFC's, which are due to anthropogenic activity, and the changes of temperature, water vapour and clouds in the tropics; which in turn primarily control the surface equilibrium temperature of the earth. I will focus my discussion on water vapour: others here will discuss the radiative effects of the clouds themselves. Water vapour is the major absorber in the infrared contributing to the greenhouse effect. Unlike the other greenhouse gases, whose global concentrations are slowly increasing because of anthropogenic activity, the concentration of water vapour is controlled by the transport and precipitation processes in clouds. Generally the water vapour content increases with temperature, because the saturation vapour pressure increases with temperature. In the tropics, water evaporates primarily from the oceans, which are heated directly by incoming solar energy, rises in cumulonimbus clouds (thunderstorms), where it condenses, releasing the latent heat of condensation and freezing. This latent heat release both drives the vertical circulation and balances the net infrared cooling of the atmosphere. The air which flows out of these storms in the upper troposphere is full of ice, which forms the extensive picturesque anvils so characteristic of thunderstorms. In the tropics, clusters of thunderstorms produce extensive anvil clouds, which are readily visible on satellite pictures. These anvils, which are often 400 mb thick, last for many hours, sometimes even a day, since they are maintained by dynamical, convective and radiative processes. As they decay and their ice crystals evaporate, they are responsible for most of the water vapour input to the upper troposphere. Estimates from GATE (Gamache and Houze, 1983) have suggested that up to 10 percent of the water which is evaporated at the ocean surface is injected into these thick anvils. Away from convective disturbances where air sinks as it slowly cools radiatively, the relative humidity in the tropical upper troposphere is around 30-40 percent up to about 350 mb, where routine radiosonde measurements become unreliable. At higher levels, the data from the Stratospheric Aerosol and Gas Experiment (SAGE-II) suggest

that the relative humidity (away from deep convection) is about 20-25 percent at 200 mb. The annual variation is small, with higher values on the summer side of the equator.

3. LINDZEN'S ARGUMENT

Lindzen (1990) has argued that there is a possibility that deep convection might dry the upper troposphere. This is important because absolute decreases of water vapour at high levels can offset the effect of increases at low levels in their greenhouse effect.

His argument is as follows. *Boundary layer temperature and moisture increase with increasing sea surface temperature, so that the tops of the deep convective clouds in the tropics will go higher.* This is correct. If the temperature at the tropopause falls, then the highest outflows from these clouds will be at colder temperatures. Since the saturation mixing ratio over ice decreases with temperature, Lindzen argues *that the cumulonimbus outflow will therefore inject drier air at the highest outflow level; and then the subsidence of this dry air between clouds will produce a drier upper troposphere.*

This idea is wrong (Betts, 1990), because deep convective clouds inject water (as ice ad vapour) into the upper troposphere at all levels above their freezing level (this is near the middle troposphere in the tropics; about 550 mb), not just at their tops. Near their highest outflow levels, most of this water is in the form of ice (the anvil clouds), so that the comparatively small value of the saturation mixing ratio plays a relatively insignificant role in the water budget at the highest levels. If Lindzen's model were right, the present upper troposphere would be very dry. In fact, the relative humidity near the freezing level in the deep tropics is about 40 percent. This is consistent with a subsidence of order 20 mb/day (which is roughly in thermal balance with the radiative cooling rate), and the injection of 10 percent of the surface evaporation as ice into the upper troposphere (mentioned above).

Lindzen's model is implausible on more general grounds. If the sea surface temperature rises in the tropics, the troposphere as a whole is warmed to a higher temperature, so that, at any given pressure, the saturation mixing ratio increases significantly. For the *absolute* mixing ratio to decrease at any level, the relative humidity must therefore *decrease significantly* (by 12-15 percent for a 2 degree C rise in sea surface temperature). The theoretical evidence is to the contrary. If the temperature warms (towards a warmer "moist adiabat") the stability of the atmosphere increases proportionally more than the increase in the radiative cooling rate, so that the mean sinking motion between the convective systems decreases (Betts and Ridgway, 1989). This reduced subsidence would tend to increase (not decrease) the relative humidity at any level (Betts and Albrecht, 1987). In this simple coupled model of Betts and Ridgway (1989), doubling $CO_2$ increased the tropical surface temperature by 2 to 3 degrees C, consistent with the increase shown by global circulation models.

Clearly, we need better observations of water vapour in the tropical upper troposphere, but the evidence we have is consistent with a relatively tight coupling of water vapour to temperature in which the relative humidity changes rather little.

4. CONCLUSION

I have concentrated on the role of water vapour in the tropics on the greenhouse effect. It is probable that water vapour, because it is coupled thermodynamically to the temperature, will increase as the temperature of the troposphere increases. This coupling leads to an important amplification of the greenhouse effect, as is shown by both global climate models (e.g. Cess et al., 1990) energy balance models (e.g. Betts and Ridgway, 1989) and observational studies (e.g. Raval and Ramanathan, 1989). The radiative role of clouds is more complex, and others here will discuss this in more detail.

As a society we have many choices, but one basic dilemma concerning climate change. The waste products of our civilization are significantly modifying the atmosphere, making it more opaque to infrared radiation. The coupling of temperature and water vapour amplify this effect, while the effects of changes in cloudiness are more complex. Modelling studies suggest that a warming of the atmosphere of several degrees will result if present trends continue. Because of the natural fluctuations of the climate system, it may be a decade or more before we can have confidence that the recent climate warming reflects a long-term trend. Because of the complexity of the earth system, our relatively simple models might mislead us, but again the improvement of our models is a steady incremental process which also takes decades.



If we wait a decade or two for increased certainty, the climate impact will be much larger, harder to reverse, and the impact on the earth's natural ecosystem may be severe. A wise society would take action now to reduce emissions to the atmosphere, in order to limit and delay the long-term impact on our climate. Much can be done at like incremental cost. The scientific community can present the evidence, but political resolve and global co-operation are clearly needed. Changing the direction of our industrial society towards one which is more respectful of its impact on our global environment will take time, probably decades, even if we begin now.

Senator GORE. Thank you very much. Dr. Hall.

## STATEMENT OF MICHAEL HALL, Ph.D., DIRECTOR, OFFICE OF GLOBAL PROGRAMS, NATIONAL OCEANIC AND OCEANOGRAPHIC ADMINISTRATION, SILVER SPRING, MD

Dr. HALL. Mr. Chairman, I am very pleased to be here today to address this important topic and I am honored to be in such distinguished company.

The statement which I have provided for the record will explain in some detail NOAA's contribution to studies of cloud-climate relationships. I will try to abbreviate for the moment and give you the quickest overview of the subject.

One thing I think is important to note in the beginning: When you look at any agency program or that set of agencies in the U.S. global change research program, in order to see the whole of the effort you have to look not only at what is being done in the name of clouds, but also what is being done in the name of water and energy balance, and aerosols, as well as the net effect of all of those variables on radiation balance.

I am implying already, I hope, that the problem is being worked somewhat piecemeal at the present time and there is an opportunity to organize better our efforts.

NOAA, by the late 1980's focused very strongly, together with NSF, and NASA, on cloud climatologies. I think by the end of the eighties we had a credible effort going in that regard; we are now moving from cloud climatology to precipitation climatology. Ultimately we must have credible climatologies of water vapor. The latter capability is some ways away and that should be cause for some concern.

Model experimentation—that is to say, the parameterization of cloud processes in models—has been going on in NOAA for a long time, as have diagnostic studies of clouds, water, and energy processes, sponsored by NOAA, in the university community, as well as at NOAA laboratories.

One other program I should mention is the Tropical Ocean and Global Atmosphere Program, which has never pretended to be about clouds and climate per se, but was investigating primarily the prediction of El Nino phenomenon and their global consequences. Yet TOGA, because of the nature of the problem in the tropical Pacific, has had to examine cloud climatology, radiation balance, air-sea exchange processes, and how they act in concert to regulate one important part of the Earth system. I think we stand to learn a great deal from that experiment.

At the present time we are focusing efforts within the context of the U.S. Global Change Research Program on organizing NOAA contributions to the Global Energy and Water Cycle Experiment—GEWEX—of the World Climate Research Program, the parallel

IGBP program in biological aspects of the hydrological cycle—BAAC, and in a new project which will be done over the Mississippi runoff basin, called GCIP, the GEWEX Continental Scale International Program. It will be the most organized effort confronting us in the 1990's, because GEWEX itself will not begin until around 2000.

In summary, Senator, the subject of this hearing is a very intimidating problem which ultimately cannot be worked piecemeal. The different pieces of the problem which we are presently working are shedding valuable insight and make it possible for us to build a higher order understanding. But I look forward to your promised discussion of how we can get more for our dollar, how we can better organize our effort, because I think at the present time getting a comprehensive, integrated attack on the problem of clouds, aerosols, radiation, water and climate is a key to the next steps in understanding climate change.

Thank you.

[The prepared statement of Dr. Hall follows:]

## PREPARED STATEMENT OF DR. J. MICHAEL HALL

I would like to express my appreciation to the Committee for the opportunity to discuss a topic that is undeniably recognized within the scientific community as the most critical area forestalling progress in our understanding of the global climate system. Climate changes may arise from natural forces within the earth system, or as a consequence pressures on our natural resources by an increasing world population, and by an increasing capacity to exploit those same resources to achieve technological progress.

The current urgency felt by the scientific community to produce accurate predictions of change under a regime of significantly enhanced atmospheric carbon dioxide and other "greenhouse" gases, has pushed computerized models of the climate system beyond a satisfactory level of credibility. Different general circulation models of the climate system, forced in identical ways, produce new "climates" that are similar in their gross characteristics, but differ significantly in detail. At a regional level, for example over parts of the continental U.S.A., the differences can be so large that conflicting guidance would be given to those planning strategies to adapt to changing climatic regimes.

Detailed studies of the root causes of these differences reveal that they are typically caused by subtle variations in the way different models attempt to mimic physical processes operating in the total global system, and by the number of such processes different models attempt to incorporate. Processes which operate at scales smaller than the spatial and temporal resolutions of the simulation models are represented by physically based but approximate mathematical schemes (parameterizations). These schemes include attempts to distribute incoming and outgoing radiant heat energy, develop the many cloud forms, allow for the presence of atmospheric aerosols, cause clouds to precipitate, and partition the precipitation into the surface components of the hydrological cycle, e.g. surface runoff, infiltration etc.

### THE SCIENTIFIC ISSUES

Clouds and water vapor together are the dominant control on the amount of solar energy reaching the earth's surface and the infrared emission to space. The "greenhouse" effect as we all know is critical for life on earth. Direct anthropogenic enhancement of other radiatively active trace gases in the atmosphere ($CO_2$, methane, chloroflurocarbons etc.) that has the potential for causing major climatic change may be amplified or diminished by feedbacks within the global energy and water cycle, especially those that affect the development and distribution of clouds. NOAA is engaged in major monitoring and research programs to improve our understanding of atmospheric trace gases that influence the Earth's chemical and radiative balance. NOAA is also committed to a climate model development program to increase skill in representing the many complex feedbacks in the global climate system.

Atmospheric aerosols are increasingly seen as an important factor in the atmospheric component of the global energy and water cycle. As a direct modulator of the greenhouse effect, atmospheric aerosols can interact with radiant energy through scattering and absorption processes. In a more indirect way, atmospheric aerosols also modulate the greenhouse effect since they are critical as nuclei for the formation of clouds and cloud properties, such as brightness enhance the ability of clouds to reflect incoming solar radiation back to space. Atmospheric aerosols are therefore a pervasive and necessary component of the climate system yet their roles are poorly represented, if at all, in the current generation of climate models. Furthermore, just as human activity is changing the background levels of some radiatively active gases, so too it is changing the levels of atmospheric aerosols. Unlike the principal radiatively active anthropogenic gases which generally become well-mixed throughout the atmosphere, anthropogenic aerosol loadings tend to have maximum concentrations downwind of major centers of population and industry. The impacts of anthropogenic aerosols on the climate system, therefore, are likely to be manifested in ways quite unlike the impacts of the enhanced greenhouse gases. NOAA scientists are engaged in research projects to monitor the sources and sinks of both natural and anthropogenic aerosols in order to assess the relative changes in concentrations. We are also working closely with other agencies on the need for a comprehensive research plan to address this complex issue.



### THE INTERNATIONAL RESPONSE

Small-scale processes in climate models such as evaporation and the formation of clouds have been collectively described as the "fast component" of the climate system. The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) have developed the Global Energy and Water Cycle Experiment (GEWEX) as a focus for this component of their jointly sponsored World Climate Research Programme (WCRP). The Tropical Oceans and Global Atmosphere (TOGA) Project and the World Ocean Circulation Experiment (WOCE) of the WCRP are concerned with longer time-scale processes of the climate system.

The nature of GEWEX is such that its objectives underpin progress on all time scales. Similarly, TOGA is primarily concerned with prediction on seasonal and inter-annual time scales, but understanding and modeling latent and sensible heat fluxes as well as radiative fluxes at the air-sea interface, are critical for getting the right distribution of clouds and cloud types in the coupled global climate models that will be used in various configurations to predict on seasonal, inter-annual and decadal time scales. The Coupled Ocean Atmosphere Response Experiment (COARE), a major field program in TOGA is planned for the Western Pacific region from November 1992 through February 1993. It will address many of the key problems in understanding why this region of the globe is such a critical area for large-scale, seasonal and inter-annual fluctuations in the climate system. However, COARE will also provide opportunities to gather data on unique features of tropical cloud systems. TOGA COARE, therefore is one of the most important initiatives in this decade directed at improving our understanding of the climate system. NOAA, NSF, NASA, ONR, and the U.S. academic community along with the scientific communities of many other nations are devoting considerable resources towards ensuring its success.

The earth's biosphere also plays a substantial, interactive role in partitioning energy and water in the climate system, and the potential exists for major impacts on the current make-up and distribution of ecosystems as a consequence of climate change. To study and understand better the sensitive balance between the physical and living components of the earth and its climate system, International Council of Scientific Unions (ICSU) has instituted the International Geosphere Biosphere Programme (IGBP). In view of the strong interaction between climate and the biosphere, the WCRP and IGBP are developing common planning processes in several key areas including the hydrological cycle. However, just as with TOGA COARE, the international agencies sponsoring these programs look to individual, national funding agencies to respond in a coordinated way to the variety of scientific initiatives being proposed to tackle the many global change research issues. NOAA plans to continue its support for many of these initiatives which include the very successful International Satellite Cloud Climatology Project, the developing Global Precipitation Climatology Project and the emerging GEWEX Continental-scale International Project (GCIP).

GCIP warrants special mention since it will enable the U.S. to offer a significant portion of its land mass—the Mississippi Basin—for an intensive large-scale climate data gathering and modeling study. In turn, the U.S. will reap the benefits of an international scientific effort to understand and model the complex hydrological cycle of this region. Skills learned in this data rich region, will help us to improve our models in those regions of the globe with poorer climatic records. Much of the

data for GCIP will come from existing NOAA data bases and observing systems, and from planned upgrades to those systems. successful GCIP will also speed the benefits of the next era of space-based remote sensing satellites.

THE NATIONAL RESPONSE

At the national level the Committee on Earth and Environmental Sciences (CEES) has strongly endorsed the international initiatives for developing better techniques to model and ultimately predict moisture, radiative and sensible heat fluxes throughout the- climate system. Climate and Hydrologic Systems continues to be rated as the area of highest priority within the U. S. Global Change Research Program (USGCRP). The role of clouds in the Earth's radiation and heat budget, and processes driving energy and water fluxes within the climate system are among the Program's highest rated topics for research. Each agency participating in the CEES process has developed a program of research and activities that reflects its own capabilities to address the issues.

Within the USGCRP the broadly stated, long-term goal of NOAA's Climate and Global Change Program is: *to establish a new national information service based on the achievement of reliable assessments and quantitative predictions of a changing global climate.* Considerations of the NOAA-wide, and even National infrastructure ultimately needed to achieve this goal have been substantial factors in developing the program. NOAA has made many contributions already to the understanding of the issue of the role of clouds in climate and is continuing to foster research within its own institutions and the academic community through a grants program. NOAA scientists are also participants in several joint research initiatives with other agencies. Integration and synthesis of climate information on a National and International scale has been a touchstone of the NOAA Climate and Global Change Program from the outset. The strong research character of the program at present is emphasized in the somewhat more narrowly conceived program objective: *to (learn how) to provide reliable predictions of global climate change and associated regional implications on time-scales ranging from seasons to a century or more.* As we have emphasized throughout this testimony/address, establishing system predictability on any time or space-scale will ultimately be underpinned by our ability to understand, model and predict those basic physical processes including particularly the role of cloud processes which drive the system. Developing a nationally supported, integrated modeling, prediction and assessment capability will be an important step to achieving this goal.

Senator GORE. Thank you very much. Dr. Tilford.

## STATEMENT OF SHELBY TILFORD, Ph.D., DIRECTOR OF EARTH SCIENCE AND APPLICATION DIVISION OF THE OFFICE OF SPACE SCIENCE AND APPLICATIONS, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. TILFORD. Thank you very much, Mr. Chairman. I am pleased to be here and I would like to speak briefly about elements of the U.S. global change program, GEWEX, as Dr. Hall discussed, and some of the efforts of NASA's Mission to Planet Earth to address some of the issues.

I think the CEES, Committee on Earth Environmental Sciences, recognized several years ago the importance of clouds and water vapor. If you look at the priorities chart within the U.S. Global Change Research Program, I think you see clouds and water vapor and aerosols as one of the highest priority items.

We have tried to set up a complementary observations process and modeling approach in which we could treat these three elements.

The Inter-Governmental Panel on Climate Change also recognized the largest uncertainties with respect to greenhouse gases are clouds and oceans. These are all coupled through the water vapor process.

As you know and have heard several times, water is the biggest unknown in the total feedback mechanism. It adds to the heating



of the planet, it adds to the cooling of the planet, evaporation, transpiration, clouds, aerosols. So, it is a very coupled process. It takes precise measurements of humidity, clouds, and aerosols, and, as you have heard several times, how you put these together, to understand their role in global change.

I think GEWEX is the first time that an organized effort has been put together to look at the global energy and water cycle. But there are also ongoing programs, such as TOGA and WOCES, which will contribute to this.

The real concern here, I believe, in terms of how we implement these programs is the rate at which we are able to implement them, because right now we are having difficulty funding TOGA and WOCES, IGAC, et cetera, at the agreed to international participation levels. We are concerned that the resources in the future may not allow rapid development and implementation of either the continental scale or the global, GEWEX, program.

Within NASA's Mission to Planet Earth, we are involved in a number of efforts. In the rescoping of the Earth Observing System, one of the biggest issues is clouds and radiated feedback, and how we address those in the most intelligent way over a long period of time. Of course we must have long-term calibration in addition to long-term measurements. Otherwise the measurements will not mean very much.

So, with this, we have tried to look at the followon to things like the Tropical Rainfall Measurement Mission, which we hope will be flown in 1997 as a joint United States-Japanese program, the flight of instruments to measure ocean surface stress, and other instruments to improve both water vapor and temperature measurements as being the highest priority elements of NASA's Mission to Planet Earth.

To do this, of course I cannot fail to note that it requires an international contribution and we plan over the next few years to work very closely with our international partners in providing as many of these measurements as possible.

Thank you very much.

[The prepared statement of Dr. Tilford follows:]

PREPARED STATEMENT OF DR. SHELBY G. TILFORD

Mr. Chairmen and Members of the Committee, I am pleased to appear before you today to discuss the role of cloud research in the U.S. Global Change Research Program (USGCRP), the Global Energy and Water Cycle Experiment (GEWEX), and how NASA's Mission to Planet Earth Program plans to address these issues.

THE U.S. GLOBAL CHANGE RESEARCH PROGRAM: GOALS AND PRIORITIES

The interagency Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) has developed the U.S. Global Change Research Program over the past five years in cooperation with the National Academy of Sciences (HAS) and a number of agency Advisory Committees and Panels. The overarching and long-term goal of the USGCRP is to establish the scientific basis for national and international policy-making relating to natural and human-induced changes in the global Earth system. To meet the long-term objectives of the USGCRP requires balance between the scientific objectives in both the short and long-term. These are:

- Observations of long-term trends, ensuring integrity of calibration
- Process studies for improved understanding
- Model development for predictive capability

The thirty year CEES objectives for the USGCRP include development of an international operational Global Climate Observing System (GCOS), and a predictive capability on a global and regional scale.

Within the CEES, a priority framework has been identified which includes Strategy priorities, integrating priorities and science priorities. In terms of the science priorities, the role of clouds, ocean circulation and heat flux, land/atmosphere/ocean water and energy fluxes, and coupled climate system links have been rated as some of the highest priority science objectives within the USGCRP.

Key uncertainties in quantifying long term climate change have been identified, quantified and put in priority order by the National Academy of Sciences (HAS) and international Intergovernmental Panel on Climate Change (IPCC) assessments.

The IPCC identified three highest priority uncertainties that need to be addressed:

- Greenhouse gases, which control the magnitude and timing of climate change, with emphasis on the carbon cycle (carbon dioxide, methane and tropospheric ozone precursors), sulfur and ozone, and the response of these chemicals to environmental change (climate and atmospheric composition)
- Clouds, which affect the magnitude of climate change (Water and Energy Cycles: clouds and radiative properties, hydrology and moist processes)
- Oceans, which affect the timing and regional patterns of climate change

Three other priority areas were identified by IPCC:

- Land-surface hydrological processes, which affect regional climate change and water availability
- Polar ice sheets, which affect regional climate change and sea level rise
- Ecological processes, which affect greenhouse gas emissions and ecosystem productivity

The U.S. and the international research communities over the past few years have consistently identified the areas of this hearing as being very important in global climate change. As a result, NASA, NSF, NOAA, DOE and the other U.S. agencies have factored these priorities into their planning for the future. Within NASA, cloud research has been a high priority objective in our planning for the Mission to Planet Earth (MTPE) and Earth Observing Satellite (EOS) Programs.

### THE GLOBAL ENERGY AND WATER CYCLE EXPERIMENT

The Global Energy and Water Cycle Experiment (GEWEX) is a program initiated by the World Climate Research Programme (WCRP) to observe, understand, and model the hydrological cycle and energy fluxes in the atmosphere, at land surface, and in the upper oceans (Attachment 1). The goal of the GEWEX program is to reproduce and predict, by means of suitable models, variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources. This data will help scientists understand the response of these processes to changes in the environment, such as an increase in greenhouse gases. GEWEX is being designed to provide an order of magnitude improvement in the ability to model global precipitation and evaporation, as well as to enable accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change.

The objectives of the GEWEX Program have been defined as follows:

1. Determine the hydrological cycle and energy fluxes by means of global measurements of atmospheric and surface properties
2. Model the global hydrological cycle and its impact on the atmosphere and oceans
3. Develop the ability to predict variations in global and regional hydrological processes and water resources, and their response to environmental change
4. Foster the development of observing techniques and data management and assimilation systems to meet the above objectives

The GEWEX Program Strategy is to:

1. Build on existing programs and data
2. Conduct modeling programs to model all aspects of the hydrologic and energy cycles with evolving, fully coupled atmosphere-land-ocean components
3. Make recommendations to the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA) and the National Space Development Agency (NASDA) (Japan) with respect to instruments planned for future space platforms
4. Conduct studies with international participation encompassing the full range of experimental scales from small scale process studies (1 x 1 km to 100 x 100 km), to continental scale process studies, to global process studies



The GEWEX Science Plan has been published and the Implementation Plan is in preparation. Both an International GEWEX Project Office and a U.S. GEWEX Project Office have been established in Washington, D.C., principally supported by NASA.

### THE U.S. ROLE IN GEWEX

In defining important projects, the Committee on Earth and Environmental Sciences (CEES) agencies have considered both the highest-priority scientific uncertainties identified by groups like IPCC, the International Council of Scientific Unions (ICSU), WCRP, and WMO as well as their own special mission responsibilities in the area of global change or climate change. The Global Energy and Water Cycle Experiment (GEWEX) of the WCRP, and the Biospheric Aspects of the Hydrological Cycle (BACH), the core project of the International Geosphere-Biosphere Program, are the primary international research efforts dealing with issues of regional climate change. The U.S. has become the major participant in both of these projects.

The GEWEX Continental International Experiment (GCIP), planned to begin operational phase in FY 1994, is designed to carry out a comprehensive study of the Mississippi River Basin. In conjunction with this and other international efforts, especially BACH, the International Satellite Cloud Climatology Project (ISSCP), and the International Satellite Land Surface Climatology Programme (ISLSCP), the USGCRP plans to support field experiments designed to obtain accurate estimates of fluxes of water, energy and other biogeochemical substances. These research projects are essential to improving the representation of the land surface processes in the integrated climate system models—a highly recommended IPCC priority.

Fulfilling the objectives of international programs such as GEWEX, the World Ocean Circulation Experiment (WOCE), the international Joint Global Ocean Flux Studies (JGOFS), and others requires resources. The U.S. continues to be looked to as the key to successful acquisition of those resources. However, longstanding, ongoing efforts like the Tropical Ocean Global Atmosphere Program Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) and the International Global Atmospheric Chemistry program (IGAC), which are producing valuable input to decisionmakers, simply cannot be abandoned to support new large programs. The CEES believes that new multifunded international programs should simply not be started until the prospect for sufficient funding can be ensured.

Current U.S. efforts in these areas are critically dependent upon the availability of sufficient resources in several USGCRP participating agencies. I am deeply concerned that the final USGCRP budget for FY 1992, and the out-year projections, will seriously jeopardize interagency and international commitments to this major research effort aimed at achieving predictive understanding of the regional impacts of climate change on water resources in the United States.

### MISSION TO PLANET EARTH (MPTE) AND CLOUD AND RADIATION BUDGET RESEARCH

A significant number of U.S. agency programs are directed to improving the current understanding of clouds and their radiative balance, including precipitation. Key programs include: (1) the Department of Energy's Atmospheric Radiation Measurement (ARM-DOE) program; (2) the emerging GEWEX program, which will conduct its first continental-scale experiment within the U.S., (NOAA, NASA, NSF, and DOI); (3) the International Satellite Cloud Climatology Program (ISCCP-NASA, NOAA, NSF); and several ongoing Research and Analysis Programs (NASA, NSF, and NOAA). These latter include the development of advanced aircraft and Shuttle lidar aerosol and water vapor measurement systems.

Development of the space component of GEWEX requires substantial investments before and during the Mission to Planet Earth era. Missions to fly in the early- to mid-1990's such as TOPEX/Poseidon, ADEOS, ERS, the Japanese Earth Remote Sensing Satellite (JERS), and TRMM provide global observational data critical to the development of the GEWEX program. One key Earth Probe is the joint U.S.-Japanese Tropical Rainfall Measurement Mission (TRMM). Current plans include measurements of the Earth radiation budget using Clouds and Earth's Radiant Energy System (CERES) instruments on TRMM (1997), on the European Polar-Orbiting Platform (1997) and the first EOS platform (1998). Cloud images and aerosol measurements are highly desirable to complement the Earth Radiation Budget measurements. Measurements of clouds and aerosols and their effect on the Earth radiation budget is critical for understanding global change. To meet this high priority need, the instruments must be well calibrated for continuity with the planned CERES measurements. A number of global data sets have been determined to be important to the GEWEX program (Attachment 2).

The Earth Observing System will establish a comprehensive, integrated program of space-borne observations that will improve understanding of Earth system processes and develop a fifteen year long-term calibrated global data set to observe natural and human-induced changes. EOS instruments under consideration to be launched first on the initial two or three platforms in the 1998—2002 time frame include several that will observe clouds and the radiative budget. These instruments have been identified by the GEWEX program as important. They include:

ACRIM—Solar output

AIRS/AMSU/MHS—Improved infrared and microwave temperature and water vapor soundings of the atmosphere

ASTER—Fine-resolution measurements of surface from visible to infrared (HIRIS on second launch)

CERES—Total Earth's radiation balance

EOSP—Tropospheric aerosols

HIRDLS—Stratospheric trace gases (ozone, methane, water vapor), stratospheric temperature, etc.

LIS—Lightning

MIMR—Microwave radiometer for sea ice, snow cover, atmospheric water vapor, and precipitation index

MISR—Multi-angle measurements for tropospheric aerosols, surface bidirectional reflectance

MODIS-N—Visible infrared global mapping of vegetation, oceans, atmospheric temperature, cloud detection and characterization

MOPITT—Carbon monoxide and methane in the troposphere

SAGE III—Stratospheric aerosols and ozone profiles

In addition, a number of the interdisciplinary investigations which have been selected for EOS have direct application to GEWEX. The following investigations are especially important:

- Global Water Cycle: Extension Across the Earth Sciences
- The Development and Use of a Four-Dimensional Atmospheric/Ocean/Land Data Assimilation System for EOS
- Long-term Monitoring of the Amazon Ecosystems through the EOS: From Patterns to Processes
- Hydrology, Hydrochemical Modeling and Remote Sensing in Seasonally Snow Covered Alpine Drainage Basins
- Estimation of the Global Water Budget
- Internannual Variability of the Global Carbon and Energy Cycles
- Hydrologic Cycle, Semi-Arid Areas, Climatologic Processes
- Investigation of the Atmosphere/Ocean/Land System Related to Climatic Processes
- Biosphere/Atmosphere Interactions
- Clouds and Earth's Radiation Budget System: Analysis (CERES-A)

## INTERNATIONAL COOPERATION

NASA is firmly committed to international cooperation in Earth science research. The questions we are studying and the problems we seek to understand are inherently global, and our international partners possess important scientific expertise and data which can contribute to our common success. EOS has been planned with this philosophy strongly in mind. It includes extensive international coordination of both the science and the technology involved. The Earth Observation International Coordination Working Group (EO-ICWG) is the primary mechanism for international coordination of EOS. Its members are NASA (with the cooperation of NOAA), the Canadian Space Agency, the European Space Agency (ESA) and Japan, led by their Earth observation offices, with participation by their operational meteorological agencies. Through EO-ICWG, the payload planning for EOS has been conducted in concert with planning for the European and Japanese platforms, to ensure rational and harmonized use of the collective assets of the partners Work is underway currently in EO-ICWG on a number of other important related coordination issues, such as data policy, data management, calibration and validation, and mission operations. EO-ICWG has provided the framework for each participant to maintain total control over his program while fully coordinating plans and taking into account partners' interests, contributions, and decisions.

On a broader level, the international coordination of the space segment of global change is the responsibility of the Committee on Earth Observations Satellites (CEOS) which was created as a result of the 1984 Economic Summit. CEOS brings together agencies responsible for Earth observations space activities, including Landsat and Systeme Pour l'Observation de la Terre (SPOT), the European Remote Sensing Satellite, ERS-1 and the Japanese Earth Remote Sensing Satellite (JERS-1), TOPEX/Poseidon, the Japanese Advanced Earth Observing System, ADEOS, as well as planned Brazilian and Indian missions. CEOS meets biennially. One of its objectives is to ensure close coordination with the international global change scientific programs such as IGBP and WCRP. The CEOS Working Group on Data has been active in defining common data formats for user products to facilitate the use of similar data from different satellites. The Working Group is also responsible for a common pilot international directory now being installed in the US, Europe, Canada, and Japan. CEOS is expected to become much more active in the next few years, and will play the lead role in international coordination of space observation programs.



## CONCLUSION

I appreciate this opportunity to discuss the GEWEX program and other efforts to understand the role of clouds in the Earth's environment. This issue is without question critical to understanding global change.

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## ACRONYMS/ABBREVIATIONS

ACRIM—Active Cavity Radiometer Irradiance Monitor
AIRS—Atmospheric Infrared Sounder
AMSU—Advanced Microwave Sounding Unit
ARM-DOE—Atmospheric Radiation Measurement—Department of Energy Program
ASTER—Advanced Spaceborne Thermal Emission and Reflection Radiometer
BACH—Biospheric Aspects of the Hydrological Cycle
CEES—Committee of Earth and Environmental Sciences
CEOS—Committee for Earth Observing Satellites
CERES—Clouds and Earth's Radiant Energy System
DOI—Department of the Interior
EO-IWCG—Earth Observations International Coordination Working Group
EOS—Earth Observing System
EOSP—Earth Observing Scanning Polarimeter
ESA—European Space Agency
FCCSET—Federal Coordinating Council for Science, Engineering and Technology
GCIP—GEWEX Continental International Experiment
GCOS—Global Climate Observing System
GEWEX—Global Energy and Water Cycle Experiment
HIRDLS—High-Resolution Dynamics Limb Sounder
HIRIS—High Resolution Imaging Spectrometer
ICSU—International Council of Scientific Unions
IGAC—International Global Atmospheric Chemistry Program
IGBP—International Geosphere Biosphere Program
IGFA—International Group of Funding Agencies
INC—International Negotiating Committee (for a climate change convention)
IPCC—Intergovernmental Panel on Climate Change
ISCCP—International Satellite Cloud Climatology Project
ISLCP—International Satellite Land Surface Climatology Programme
JERS—Japanese Earth Remote Sensing Satellite
JGOFS—Joint Global Ocean Flux Studies
Lidar—Light Detection and Imaging
LIS—Lightning Imaging Spectrometer
MHS—Microwave Humidity Sounder
MIMR—Multifrequency Imaging Microwave Radiometer
MISR—Multi-Angle Imaging Spectro-Radiometer
MODIS-N—Moderate Resolution Imaging Spectrometer-Nadir
MOP ITT—Measurements of Pollution in the Troposphere
MPTE—Mission to Planet Earth
NAS—National Academy of Sciences
NASA—National Aeronautics and Space Administration
NASDA—National Space Development Agency (Japan)
NOAA—National Oceanic and Atmospheric Administration
NSF—National Science Foundation
SAGE-III—Stratospheric Aerosol Gas Experiment—III

TOGA-COARE—Tropical Ocean Global Atmosphere Program—Coupled Ocean-Atmosphere Response Experiment
TOPEX/Poseidon—Ocean Topography Experiment (U.S./France)
TRMM—Tropical Rainfall Measurement Mission
UNEP—United Nations Environment Program
UNESCO—United Nations Educational, Scientific and Cultural Organization
USGCRP—United States Global Change Research Program
WCRP—World Climate Research Programme
WMO—World Meteorological Organization
WOCE—World Ocean Circulation Experiment

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ATTACHMENT 1

## The Complex Role of Water in Climate Processes

ATTACHMENT 2

## Types of Global Data Needed for GEWEX

**Basic meteorological parameters**
- Atmospheric temperature and humidity
- Ocean surface temperature, stress and topography
- Surface meteorological observations

**Tropospheric wind vector**
- Global Doppler wind lidar
- Upper air winds

**Precipitation**
- Global rain radar data
- Rain gauge and land-based rain radar data
- Ocean salinity

**Radiation and clouds**
- Solar irradiance
- Spectral outgoing long-wave radiation
- Reflected solar radiation at the top of the atmosphere
- Net flux at the surface
- Earth radiation budget
- Greenhouse trace gases
- Aerosols
- Stratospheric water vapor
- Cloud amount, type and heights of base and top

**Land surface data**
- Surface albedo and roughness
- Skin surface temperature and emissivity
- Vegetation index
- Snow cover, depth and water content
- Soil moisture and water runoff

Senator GORE. Thank you very much, Dr. Tilford. Colonel Townsend.

**STATEMENT OF COL. RONALD TOWNSEND, Ph.D., CHIEF, WEATHER PLANS, DIRECTORATE OF WEATHER, HEADQUARTERS, U.S. AIR FORCE, DEPARTMENT OF DEFENSE**

Colonel TOWNSEND. Thank you, Mr. Chairman, distinguished members of this panel.

It is indeed a pleasure to participate in this discussion of the role of clouds in climate change. I offer a perspective of what the Air Force currently has to offer in terms of satellite data and cloud data bases that may apply to research in this area.

The Air Force, through the Air Force Global Weather Central at Offutt Air Force Base, Nebraska, collects and processes weather satellite data and weather observations on a continuous basis to update a global cloud data base every 3 hours.

With respect to satellite data, we have the Defense Meteorological Satellite Program. There are normally two satellites in polar orbit providing visual and infrared imagery. With the transition to automated soft copy display at the Global Weather Central, the archive of hard copy imagery is not complete. However, we are planning to implement the capability to archive digital DMSP data by February 1992.

Global Weather Central uses the satellite data and weather observations to build a global cloud data base in real time. This cloud data base is forwarded to an Air Force operating location collocated with the National Climatic Data Center at Asheville, NC.

The cloud data base is unclassified and is available for access by any agency through the National Climatic Data Center. As a specific example, the real time nephanalysis has evolved as the Air Force's most sophisticated cloud data base. This data base contains global information on cloud type, altitude of cloud bases and tops, and total cloud coverage valid at 3 hourly increments for each day.

The Global Weather Central generates this data from conventional surface weather observations, upper air soundings, and sat-

ellite data. The data base is available for the period of record from January 1984 to the current time.

Recognizing the national interest in cloud data, the Geophysics Directorate of Phillips Laboratory has helped develop a cloud information reference library and archive. This online computer listing describes the availability and contents of government and nongovernment cloud data bases. The initiative recognizes the need for close cooperation between the Department of Defense and other agencies to share this type of data.

Thank you, Mr. Chairman, for inviting me to participate in these discussions. We are ready to assist in providing any data that we have that may be applicable to the study of clouds and global change.

Senator GORE. May I say just in following up on Colonel Townsend's statement, thank you for being here Colonel Townsend. It is my impression that cloud and water vapor researchers are already aware of the data bases collected by the Air Force, but have made less than the fullest use of this data, partly because it is in rougher form than is desirable and useful for the investigations currently underway, partly because the data is not as easily accessible, nor is it configured in a form which makes it optimally useful to researchers.

One of the things I hope will come out of this series of inquiries by the subcommittee is how those who manage data bases like the ones that Colonel Townsend has described, and that Dr. Tilford and Dr. Hall are collecting and managing, can configure and improve those data sets in ways that will make them more useful and accessible to those of you around this table who need it and can put it to good use.

So, we want to serve here on the subcommittee, as a communication link between those who collect, store, and manage data, and those who use it. So as you learn more about these data bases, do not automatically assume that the obstacles you confront in accessing and using the data are unmovable. Many of these obstacles are movable.

I have found with the military, NOAA, and NASA, they are eager to understand how they can be more helpful and responsive to the research community. And we on this subcommittee are interested in making sure that we provide the resources in that area particularly. And on the Armed Services Committee, as I mentioned earlier, in the case of the military, there is a special pool of funding especially for that purpose.

Before I begin questions, I want to recognize the ranking Republican member of the subcommittee, the very honored Senator Pressler, who is present this morning. I invite him to make a statement.

## OPENING STATEMENT OF SENATOR PRESSLER

Senator PRESSLER. Mr. Chairman, I have an opening statement I will place in the record.

I am particularly interested in the issue of, assuming that clouds tend to slow global warming, whether there are any scientific techniques for increasing global cloud cover, and also, the degree to which global warming can mean dramatic climate changes for people around the world. I am especially concerned about the prospect of droughts, since farmers in my State of South Dakota already have had a difficult time in many years.



Using a worst case scenario, how would global warming affect farmers and others in South Dakota and other Farm Belt States? That may seem a bit parochial, but I think it carries over to agricultural production throughout the world, which is a key issue, of course, at this time.

Mr. Chairman, I have an opening statement for the record and I just want to listen here mostly.

[The prepared statement of Senator Pressler follows:]

### PREPARED STATEMENT OF SENATOR PRESSLER

Mr. Chairman, I want to thank you for holding this hearing on the role of clouds in global warming and climate change. Mr. Chairman, I want to commend you on your leadership in this important area.

In April, this subcommittee was told that the average global temperature could increase from 3 to 9 degrees Fahrenheit by the middle of next century. If carbon dioxide levels double, a nine-degree increase could mean a significant rise in the number and severity of floods and droughts and cause sharp rises in sea levels. Representing South Dakota, I am especially concerned about the prospect of droughts since many of our farmers are already in economic peril.

I believe that we need to expand our knowledge of the dramatic climate change that could affect our planet's future. There is considerable debate in Congress—the scientific community—and elsewhere about whether the time is ripe for us to fashion remedies to curb global warming before scientists understand the scope and dimensions of that threat. However, we all agree that we need a strong commitment to research enabling us to understand global warming and to predict this trend.

I note that the Bush administration has targeted global change research as a priority. In its FY 1992 budget requests the President allocated more than $1.2 billion to the U.S. Global Change Research Program. In this program, NASA, the National Science Foundation, the Commerce Department and many other agencies are combining research skills and satellite technology to find answers to key global change questions. South Dakota's EROS Data Center is going to play an important role in this effort. The center will archive much of the record amount of data that will be generated by NASA's "Mission to Planet Earth."

I am pleased that a chief priority of the administration's program is research on the role of clouds in global warming. Clouds appear to be a "wild card" in predicting global warming. This is mainly because clouds both cool the Earth by reflecting solar heat and warm the Earth by absorbing heat radiating from its surface. Furthering complicating this is the fact that global warming itself increases cloud formation. However, we must determine the significance of clouds in the climate process to develop reliable climate models to accurately predict global warming.

I look forward to hearing from our distinguished panel of global change scientists about the latest developments in cloud research and what more needs to be done. I also hope that today's panel include some discussion on the possible consequences of dramatic global warming particularly in agricultural States like South Dakota.

Again, Mr. Chairman, I thank you for holding this hearing on global warming.

Senator GORE. Thank you very much, Senator Pressler.

Let me ask all of you to assume that Senator Pressler and I cannot follow the scientific terminology and would be greatly helped if you could translate some of this into plain English. I know that is difficult, because the subject is inherently opaque and has been explored with a specialized vocabulary that is not easily translated into everyday English.

But to the extent it is possible to do that, please help us to understand the basic concepts that are at work here. I am not a scientist. Senator Pressler is not a scientist. Our colleagues on this committee are not scientists. And yet we have to advise the Senate as a whole on scientific priorities. So we do need your help in explaining science in plain English, to the extent that that is possible.

Now, I have asked the staff to reproduce a figure over here.

[A chart was shown.]

Senator GORE. It is from an article in Scientific American written by Dr. Stephen Schneider, on climate modeling. If anybody has any problem with it, please let us know. I refer to it presently in case anybody wants to make use of it. We will undoubtedly learn most, however, from your ability to explain elementary points to us.

Now, as I understand the issue here, and there are many, water vapor exists in clouds, but also in the atmosphere outside of clouds. Correct? Water vapor which is not embodied in clouds has a warming effect on the Earth as it increases in volume, correct? Is everybody agreed on that?

[No response.]

Senator GORE. All right.

Dr. LINDZEN. In amount.

Senator GORE. In amount, rather than volume. Thank you, thank you.

As the total amount of water vapor not included in clouds, increases, that definitely has a warming effect and a greenhouse effect. Now, where water vapor is embodied in clouds, it can have both a warming effect and a cooling effect, correct? Am I OK so far?

Dr. ARKING. Yes. You have to distinguish between the water vapor, which is a gas, and the cloud particles. The cloud particles is something that can give you both a cooling and a warming. It cools because it reflects all the radiation. It warms because it acts like a greenhouse gas.

Senator GORE. OK, thank you.

Even within clouds, or let us say, water vapor embodied in clouds. Clouds are made up of water vapor. The term "water vapor" is inherently a little confusing. Water vapor is a gas.

Dr. ARKING. Right.

Senator GORE. Clouds are made up of water vapor and liquid water droplets.

Dr. LINDZEN. And ice.

Senator GORE. And ice, thank you.

Now, the gas part of the water vapor in clouds is also a positive feedback to warming, which leads to further warming. If there was any way to separate water vapor out from the rest of the cloud, that would be the case. Correct?

Dr. ARKING. Yes.

Senator GORE. Now, the water in clouds, which is in drops, droplets and ice, can be both heating and cooling, correct?

Dr. ARKING. Yes.

Senator GORE. Now, what determines the difference? Clouds have a property known as optical thickness, correct? This then describes the amount of the sun's radiation capable of penetrating through the clouds. Am I OK so far?

Dr. ARKING. Yes.

Senator GORE. OK, now when some of the sun's radiation is reflected off of the clouds, back out into space, that phenomenon causes a cloud to be cool, instead of warming. Correct?

Dr. LINDZEN. Yes.

Senator GORE. What determines the optical thickness of clouds is the amount of water vapor, the amount of water in the cloud, the manner in which the drops and the droplets and ice are packed together in the cloud, and what else, the pressure?



Dr. CESS. Their size, the size of the droplets.

Senator GORE. The size of the droplets.

Dr. LINDZEN. The proportion of ice and water.

Dr. TILFORD. The altitude.

Senator GORE. I am getting to that. But does that affect the optical thickness?

Dr. RAMANATHAN. No, it does not.

Senator GORE. No. Does anything else affect optical thickness?

[No response.]

Senator GORE. All right, the presence of other particles. Does it make a difference whether these particles have a nucleus or not, or whether the droplets have a nucleus or not?

Dr. CHARLSON. They do have a nucleus.

Senator GORE. Do they always have a nucleus?

Dr. CHARLSON. Always, yes.

Senator GORE. Now, let me stop right there. Hold on a second.

So there is a difference between gas in the atmosphere, water vapor, and water embodied in drops. Is there a difference between drops and a droplet?

Dr. ARKING. No, not really.

Senator GORE. All right.

Between drops and ice? One of the things that makes that difference is the presence of nuclei, a pearl. An oyster does not make a pearl without a little grain of something to irritate it and around which the pearl can coalesce. Correct? And raindrops and cloud drops are formed pretty much the same way. Correct?

Dr. CHARLSON. Raindrops are formed from the coalescence of large numbers of cloud droplets.

Dr. LINDZEN. In warm rain.

Dr. CHARLSON. In warm rain, yes.

Senator GORE. So, there is a difference between drops and droplets.

Dr. CHARLSON. Raindrops fall.

Senator GORE. When they are in the cloud they are droplets. But when they fall as rain, they are drops. I mean they are much bigger, by at least a factor of 100 or so.

All right, I have you.

Now, repeat what you said, Dr. Charlson, about droplets, drops, and nuclei.

Dr. CHARLSON. Each droplet in a warm cloud—which is the simplest possible case—each droplet forms on an aerosol particle, which is water-soluble, and acts as a nucleus of condensation. The number of aerosol particles with certain water solubility properties determines how many droplets form in a given cloud.

Senator GORE. OK.

Dr. CHARLSON. Even for a constant amount of liquid water in that simple cloud, you can have very different reflectivities for solar radiation, depending on the population or the number of these aerosol particles with these special properties which we call cloud condensation nuclei.

There is a great sensitivity of the reflectivity of the cloud to the number of these cloud condensation nuclei. A 30-percent increase

of cloud nuclei, only over the oceans, only influencing low stratus clouds, is calculated to cool the entire planet by about 1 watt per square meter. So, there is a great sensitivity there.

Senator GORE. I thought that you were talking about the Northern Hemisphere first. Were you not?

Dr. CHARLSON. Earlier I referred to the direct effect. We are now talking about what is called the indirect forcing, which is another function of aerosol particles in the system.

Senator GORE. Let me just pause at this point and ask you a couple of questions about these nuclei.

Correct me if I am wrong. You specialize in the microphysical properties of clouds. Now, much has been said recently about this phenomenon you just referred to, the apparent climate-cooling effect of $SO_2$ emissions, sulfur dioxide.

Dr. CHARLSON. That is correct.

Senator GORE. Presumably predicated upon the connection between sulfur emissions and cloud formation.

Dr. CHARLSON. There is both a direct effect of the reaction products of $SO_2$, sulfate aerosol, reflecting light into space. That is the haze you observe when you fly over eastern North America. You look down and you can see the ground through a haze. It is well known that the haze is primarily sulfate compounds. That is what has the direct effect, which corresponds to about 1 watt per square meter, when averaged over the Northern Hemisphere. However, it is very inhomogenous.

Now, the other effect, the indirect effect—which we cannot quantitatively treat, other than in very simplistic models at this point—is one which is a major question marks in the issue of how clouds influence climate.

Senator GORE. Now, the nuclei. You are talking here about sulfur dioxide. There are natural nuclei in the system, correct?

Dr. CHARLSON. Yes.

Senator GORE. There is one called dimethylsulfide.

Dr. CHARLSON. Dimethylsulfide is produced by certain species of organisms in the ocean.

Senator GORE. Plankton.

Dr. CHARLSON. By plankton. It goes into the atmosphere, where it reacts to produce the sulfate aerosol with the same properties as the aerosol produced from the industrial emissions of $SO_2$. The only difference is the amounts. I think maybe the numbers will help you here.

The global emission by phytoplankton—which is not very well known, but it has been worked on by NOAA scientists—is about 30 megatons of sulfur annually, 30 units. Anthropogenic $SO_2$ sulfur emissions presently are about 70 or 80. And, of course, that is all in the Northern Hemisphere.

Senator GORE. All right.

Dr. CHARLSON. The Northern Hemisphere sulfur budget is very highly influenced by the industrial activities of humans. The question is, what does this do (*a*) with regard to the direct effect; and (*b*) with regard to the indirect effect?

Senator GORE. Now, what, in fact, do your recent findings on the anthropogenic $SO_2$ emissions indicate in terms of this sulfur-driven



cooling effect in the face of a global warming caused by rising levels of greenhouse gases?

Dr. CHARLSON. I have a figure which I could put up on the easel that might assist you in that.

Senator GORE. Well, just give it to us orally, if you would.

Dr. CHARLSON. OK, $SO_2$ reacts in the atmosphere to make sulfuric acid and sulfate aerosol, producing an aerosol-optical depth of substantial magnitude over large portions of the Northern Hemisphere.

The sum-total of that, when averaged over the Northern Hemisphere, produces about minus 1 watt per square meter change of the Northern Hemisphere heat balance.

However, it is not uniform. That to compare that to the greenhouse warming, Professor Cess has given me a good way of putting it—and he can correct me if I misquote him—the greenhouse effect is, first of all is present over the entire globe; and is perhaps most effective in the polar winter in modifying the surface temperature of the Earth.

This aerosol effect is most effective in the midlatitudes in the summer, in the daytime. These do not coincide. So, even though in the average they may appear to cancel each other, they do not, on any kind of regional-scale basis.

The meteorological consequence of that, of a nonuniform forcing factor, are unknown at this point—in other words, the dynamical consequences—if any.

Senator GORE. So, it is, you might say, localized?

Dr. LINDZEN. It is regional, over horizontal distances of 1,000 or a few thousand kilometers.

Again, I have a map that would illustrate this for you.

Senator GORE. OK, I did not want to limit you on that. I thought if it was just a number, you could give it to us.

Dr. CHARLSON. Perhaps someone could put this up on the easel.

Senator GORE. The staff will help you out there.

Dr. CHARLSON. All right.

[A chart was shown.]

Dr. CHARLSON. This is from a computer model from a Northern Hemisphere anthropogenic sulfur cycle, performed by scientists at my institution, at Stockholm University, and at the Max Plank Institute in Mainz.

And these are the calculated amounts of loss of solar energy by reflection of aerosol alone. This does not include the cloud effect. This is just the direct effect, with a maximum of about 2 watts per square meter, here in Washington, DC, for the annual average; and over the Eastern Mediterranean, around 4—just to give you a picture of this geographically non uniform forcing.

Senator GORE. Thank you. You can take that back down. He will get it for you.

If you could go back I want to ask you, in your best judgment, about the relative effects of this mechanism versus the warming effect of increased greenhouse gases.

Dr. CHARLSON. These two, which may appear to cancel each other in the hemispheric or global average, cannot simply cancel each other because of this geographical distribution I just showed you.

That is, the title "global warming" is something of a misnomer. That is, we are not so much concerned about the average temperature of the planet, as we are about the distribution of the weather around the planet.

So, I do not think it is very useful to think about it that way.

Senator GORE. Well, of course, but the distribution of weather could be affected by a global warming.

Dr. CHARLSON. Certainly, but we expect it to be affected also by geographically dependent forcing.

Senator GORE. The regional forcing?

Dr. CHARLSON. Yes.

Senator GORE. But overall, what is your judgment about the relative power, the relative effect of global warming due to increased greenhouse gas concentrations, versus the cooling effect, regionally and locally, from $SO_2$ emissions?

Dr. CHARLSON. There are two points I would like to make in response. First of all, this accidental masking of the greenhouse warming, averaged over the Northern Hemisphere, just now happens to produce an approximate compensation over the Northern Hemisphere. It is very unlikely to continue in approximate balance because of the rapid growth of other greenhouse gases. Besides $CO_2$, there are methane, nitrous oxide, the chlorofluorocarbons, et cetera.

The second point is this forcing of which I just spoke occurs only over the Northern Hemisphere, so that the greenhouse warming of the Southern Hemisphere is essentially unaffected. The warming of the ocean's surface, should that occur, the rise of sea level caused by that, should that occur, would go on essentially unaffected by this forcing.

Senator GORE. OK, so if I could restate your response in order to simplify the climatic phenomenon which you described involving sulfur dioxide, it is that, in your judgment, the cooling effects of sulfur dioxide are significantly less than the expected increased in global warming due to increases in greenhouse gases.

So, that on balance, you would expect an overall global warming as a result?

Dr. CHARLSON. We would expect warming, ultimately. Certainly if we cut down the emissions of $SO_2$, as is presently planned, we will expect accelerated warming from the already-existing greenhouse gases.

And a long-term forecast suggests that the greenhouse gases will rather soon transcend the effect of the sulfate aerosol.

Senator GORE. All right, now let me come back to the line of inquiry that we had embarked upon before we took this detour to explore sulfur dioxide as a source of nuclei.

Dr. Tilford anticipated the next element in this. I say "we" have established by consensus, "we" are learning, what the agreed-upon state of knowledge in the research community is the role of water vapor and clouds, and their overall effect. In the case of water vapor itself, the effect is warming as amounts increase. But the effects can be both warming and cooling, as in the case of water in clouds and water and ice in clouds, depending upon the optical thickness of the cloud, a function of several factors—including the packing of droplets, ice, and other factors.



But when looking at clouds, which have the potential to both warm and cool the altitude of the clouds makes a difference. Correct?

Dr. ARKING. Big difference.

Senator GORE. Now, the altitude of the water vapor also makes a big difference, correct?

Dr. ROSSOW. Let me say that you need to be a little more precise. It is really the temperature that those two things—clouds and water vapor—are at, not their altitude, that is important.

For example, the highest clouds, on average, are in the tropics. But the coldest clouds are at midlatitudes, and cooler regions.

Senator GORE. Say that again.

Dr. ROSSOW. The effect of the clouds upon the radiation depends on their temperature, which, of course, is related to their altitude; but, since temperature varies on Earth from hot at the equator to cold at the pole, the same cloud at the same altitude would have a different temperature, depending on where it is.

So, it is really the temperature you need to know to determine the radiation effect.

Senator GORE. But does not the altitude, itself, have an impact, independent of this phenomenon?

Dr. ARKING. No.

Senator GORE. No?

Dr. RAMANATHAN. If I may, the main reason the altitude impacts is because as you go higher and higher, it gets colder and colder.

Senator GORE. Yes.

Dr. RAMANATHAN. So, these clouds that are trapping the radiation coming from the warmer ground, reradiate it at the colder temperature. So, the greenhouse effect of the clouds keeps increasing.

Senator GORE. Why?

Dr. RAMANATHAN. Because as you are lifting the altitude, the cloud-top temperature becomes colder. So, the energy it gives off to space keeps decreasing rapidly, as you are moving up.

So, the energy the planet loses to space decreases as you move the cloud to higher altitude. As Dr. Rossow is pointing out, the reason the altitude becomes a factor is temperature is linked with altitude.

Senator GORE. I see. I see.

But that linkage is elastic at different latitudes. Correct?

Dr. RAMANATHAN. Yes, yes.

Senator GORE. Is that relationship fairly steady?

Dr. ARKING. It depends on season and latitude.

Senator GORE. It depends on season and latitude.

Dr. ROSSOW. It is quite variable with season.

Senator GORE. Dr. Lindzen.

Dr. LINDZEN. There is one more issue which Professor Cess brought up. There is probably a certain confusion, if you speak of one thing warming and another thing cooling and warming. This can be true. But our concern is in what direction do any of these change under climatic forcing?

So, for instance, a process that is warming, if it diminishes under warming, becomes a cooling process. A process which is cooling, which diminishes under warming, is a warming process.

Senator GORE. All right, that is very helpful.

Dr. BETTS. To make one more thing clear here, perhaps we should clarify some terminology. I am not sure everyone is clear in all this discussion of temperature that this is concerned with the thermal radiation, the radiation that things emit because they are warm.

If you put your hand over a wood stove, you feel the radiation from that. And that is a temperature-related phenomenon. This is related to the greenhouse effect that was referred to by Dr. Ramanathan. That is the temperature of bodies that are opaque to thermal radiation determines the emission of that radiation to space.

So, how much energy the Earth loses, depends on the temperature of the highest absorber.

Senator GORE. I see.

Dr. BETTS. That is if it is a cloud. Then that controls the emission to space. And if it is a cold cloud, then less radiation escapes to space. So, it has a warming effect.

The effect in the shortwave, the solar radiation, is the visible effect of clouds: if the scattering of light by the clouds—some of which is scattered back into space. And loosely speaking, that is not related to the temperature, and it is not related to where the clouds are in the atmosphere. It is related to the internal properties, essentially the visible properties of the cloud: the drop and ice crystal structure.

Senator GORE. OK, let me summarize that point, and you tell me if I am wrong.

Earlier, I talked about clouds having the potential to both warm and cool. And focusing in on the way clouds can have a cooling effect, I improperly narrowed the point to that of reflecting the shortwave radiation coming in from the sun.

Whereas, the second way that clouds can have a cooling effect is through the radiative mechanism, whereby clouds lose heat off at the top.

Dr. BETTS. No, no.

The first thing is correct. From the point of view of the planet, the light, the solar energy that the clouds scatter to space is a cooling mechanism. From the point of view from the planet, the question of how much thermal radiation is lost to space is, in fact, the reverse.

If the clouds are higher, so that they radiate at a colder temperature, they radiate less energy to space. Then the planet stays warmer.

You are aware—for example—of how it gets cold and frosty on clear nights when there is little water vapor in the atmosphere, or no cloud in the atmosphere. The Earth can cool to space, and the surface cools.

If you have clouds up there, they will trap that radiation and emit less radiation to space. And the Earth will not cool at the surface.

Senator GORE. OK, so at any given temperature, a cloud that is higher will have more of a warming effect than a cloud that is lower. Correct?



Dr. ROSSOW. Not if it is at the same temperature. You said at a given temperature.

Senator GORE. I am using temperature in an imprecise way.

Dr. ROSSOW. That is right.

Senator GORE. At any given temperature within the atmosphere, a cloud that is higher will have more of a warming effect than a cloud that is lower. Anybody disagree with that?

[No response.]

Senator GORE. All right.

Dr. ARKING. There is one clarification. When we talk about the temperature of the cloud, we really should talk about the temperature difference between the cloud and what it would be in a clear sky region.

So, just the temperature alone, does not determine whether it is going to be a warming or a cooling effect. But it is the contrast.

In other words, if you add a cloud then the difference between the temperature of the cloud and the effect of a clear atmosphere is what determines the impact of the cloud on the radiation. For that reason, when you go to high latitudes, where the temperature profile is not as steep, then the clouds coming or going tend to have less of an infrared effect, or greenhouse effect, because the difference between the cloud-top temperature and the surface is not as much.

When you get to the tropics, the temperature drops very steeply when you get up to the top of the troposphere. Then you have a very big contrast between the temperature at the top of the high clouds and the ground, and you have a very strong radiative effect—a very strong greenhouse effect.

Senator GORE. Let me call on Dr. Ramanathan first, and then I will call on you, Dr. Lindzen.

Dr. RAMANATHAN. I think that is a pretty important point. The difference between the surface temperature and the cloud-top temperature is one fundamental parameter which governs the greenhouse effect of clouds. We have found in the Earth radiation budget measurements, for that very reason, the tropical convective clouds, which are these huge ice crystal anvils, trap an enormous amount of radiation.

Senator GORE. If you could hold off on your point for one minute, because this is the ideal time to explore this question, and then next we will turn to the point that you want to make here, Dr. Lindzen.

In May of this year, Dr. Ramanathan, the New York Times had an article on some of your research on this point indicating that there is a feedback between clouds, sea surface temperature and water vapor that seems to set an upper limit for ocean temperatures in the tropics. Now, could you briefly explain the operation of that system?

Dr. RAMANATHAN. Before that, if I can just take a minute to show what we did in the Earth radiation experiment, because it is very important in this discussion.

If you define the greenhouse effect not in terms of temperature change or global warming but the amount of heat radiation trapped in the system, then that quantity is observable and that has been determined from the Earth radiation budget experiment. One of

the important results which we obtained is that the energy trapped in the system increased significantly when you go from the cold polar oceans to the warm equatorial oceans. I can show you some dramatic pictures of those if you are interested.

But the rate of rise of the total energy trapped in that atmosphere—clear atmosphere—was quite consistent with the thermodynamic explanation of how water vapor in the atmosphere increases with temperature. This does not necessarily give a proof for the water vapor feedback in terms of global warming. What it does demonstrate, in my mind at least, is that, the thermodynamic theory is a fundamental property of the present climate.

Senator GORE. Now, hold on just a second. I do not want to interrupt your narrative here, but again, keeping it on an elementary level. When the temperature increases at the surface of the sea, more water vapor goes into the atmosphere. Correct?

Dr. RAMANATHAN. Yes.

Senator GORE. Anybody disagree with that?

Dr. RAMANATHAN. But there is one point, a caveat.

Senator GORE. This leaves aside the altitude at which the water vapor comes to reside for a few days, or a week, or whatever.

Dr. LINDZEN. It enters the lowest 2 kilometers.

Dr. RAMANATHAN. The lowest 2.

Senator GORE. It enters the lowest 2 kilometers, OK.

Dr. RAMANATHAN. We know that in the lowest 2 kilometers the water vapor increases when the sea surface temperature increases, but what we do not know is what happens at the upper levels. The problem is lack of any observations which we trust, but this is where the radiation trapped is an important indicator of what is happening.

Senator GORE. In the upper troposphere?

Dr. RAMANATHAN. Yes. What we are looking at is not necessarily the radiation trapped in the first 2 kilometers. The way the ERBE observations is used to pull out the greenhouse effect is as follows: Imagine the ocean surface. Once I know the sea surface temperature, I know exactly within a percent how much energy is radiated by the surface.

So, the surface emission is obtained from the known observations of sea surface temperature. We use the fundamental law of physics to estimate the emission from the ocean, and the satellite measures the ultimate energy escaping into space. So, we simply difference these two quantities, to obtain the energy trapped.

What we get from this technique is the energy trapped by the entire column. I cannot tell you which layer in the atmosphere is contributing the most; particularly when I examine the increased trapping from the cold polar oceans to the warm equatorial oceans. I cannot tell you where that increase is coming from, but I know that if there is any severe readjustments of the water vapor profile through the dynamics, which of course it does, it is not overwhelmed by the overall thermodynamic change, of water vapor increase with sea surface temperature.

I would like to just finish those two points, because there are a lot of discussions of the water vapor feedback.

Senator GORE. The last point, while you are collecting that, is that the ERBE data show an increase in radiation trapped.



Dr. RAMANATHAN. Yes.

Senator GORE. When you compare the data over warm oceans as opposed to over polar oceans. Correct?

Dr. RAMANATHAN. Yes; in fact, it shows a continuous rise. That is, we plot the trapping as a function of sea surface temperature. There is a significant variation, and that is why we know the dynamics are very important, as Dr. Trenberth mentioned, and as Dr. Lindzen keeps emphasizing, that we see a monotonic rise when we go from the polar oceans that are at 60 degrees latitude to the equatorial oceans.

Senator GORE. You believe that is a proxy for the greenhouse effect?

Dr. RAMANATHAN. It is a proxy for the greenhouse effect in the following sense, that this coupling between the water vapor trapping and sea surface temperature is important in determining the present day climate.

Senator GORE. OK. We will have a chance to go back to this, but I want you to go to the narrative that I interrupted, and then we will go to Dr. Lindzen. Go ahead.

Dr. RAMANATHAN. I would like to conclude. First of all, this increase in the water vapor trapping with sea surface temperature, we have found subsequently to be here for all the months—the original paper published by my student and myself in 1990 was based on 1 month, and obviously there were a lot of criticisms.

Subsequently it has been repeated with different satellite date by Professor Stephens of Colorado State University, and he finds a similar rise, and it has also been done for all the months, and we also looked at it for a 60-month period, and we see this consistent rise of the greenhouse effect with the SST, again not to be confused with the global warming for the present-day climate.

At least in my mind that the data demonstrates that the thermodynamic theory is one of the properties of the present Earth climate. I would like to make a brief statement of the implications for global warming from my written testimony. The hemispherical or global rate of increase of the greenhouse effect with SST as estimated from the ERBE data for the present climate is within 20 percent of that predicted by the climate models that yield between 2 to 4 degrees warming.

This agreement by itself does not necessarily demonstrate proof, or even convincing evidence for the positive amplification of the water vapor feedback in the global warming context. We are looking at present climate, and we are also a long way away from establishing such a proof.

However, the following two results provide a compelling evidence for the positive water vapor effect. First, the mean rate of rise of SST in the control—present—climate is similar to that in the observed data. Second, more detailed studies of the ERBE data and other data have shown a similar rise of the greenhouse effect with sea surface temperature obtained by correlating monthly variations.

Initially, we were looking at spatial variations. Now we are looking at monthly variations for each location in the ocean. For nearly 60 months of available ERBE data, each location in the ocean does show similar rise.

Now, I think there is one point—if Dr. Lindzen wants to correct, he may. I think he misspoke when he said water vapor is 98 percent of the total feedback effect.

Dr. LINDZEN. I did not say feedback—I said greenhouse.

Dr. RAMANATHAN. Greenhouse effect. That is not correct. It depends on how you define the greenhouse effect. If you define it in terms of the energy trapped in the atmosphere, then this is what we would estimate taking the ERBE data, and then we know that the clouds trap——

Dr. LINDZEN. By the way, I said water vapor in layer clouds.

Dr. RAMANATHAN. OK. Still a problem. [Laughter.]

Clouds contribute about 15 to 20 percent. This comes from the ERBE data and also the NIMBUS 7. Methane, nitrous oxide, ozone, and several other gases contribute about 3 to 5 percent of the total trapping, carbon dioxide at least 15 to 20 percent, so water vapor in the gaseous form is only about 50 to 60 percent, clouds another 15 to 20. So, between water vapor and clouds it is probably about 70 percent. There is still a large fraction due to carbon dioxide and the other trace gases.

Senator GORE. This is at a level of detail even lower than, even finer than, the one I thought we would discuss, but it is only fair to give you a chance to respond to that, Dr. Lindzen. We have got more important debates to pursue here, but if you want to address that one——

Dr. LINDZEN. The thing I originally wanted to speak to was not this, but just with clouds and their visible effect. It is not entirely appropriate to say it is independent of temperature, since it is highly dependent on the balance between liquid water and ice.

Dr. RAMANATHAN. That is true, yes.

Dr. LINDZEN. And so you often get, even though the greenhouse effect on high clouds increases, the increase from ice may come from reflectivity, so as to make it not so clear whether high clouds and low clouds behave in a certain way.

As concerns Ram's remarks, there are, of course, many ways of looking at it. I think one problem is, if you took an atmosphere that did not have the minor greenhouse gases, just had water vapor and layer clouds, you would indeed get over 98 percent of the present greenhouse effect. That is to say, if you took the others away there would be an imperceptible change.

Dr. RAMANATHAN. But that is not Planet Earth, though.

Dr. LINDZEN. What I am saying is, Planet Earth without those gases would have almost the same greenhouse effect as with them.

Dr. ARKING. The idea is, it is not linearly. They do not add up one after the other.

Senator GORE. They interact.

Dr. ARKING. They combine and they interact, so taking away a few of those gases may have a much smaller effect than you might expect.

Senator GORE. I want to pursue this, then I want to get into this larger question. With respect to the particular phenomenon that you described—that was reported on—and summarized here, I got the impression that the sea-surface temperature regulating mechanism you described might have the potential for being a rheostat



where global temperature is concerned. Is that your impression or not? I mean, is that the thrust of what you are saying?

Dr. RAMANATHAN. No, I did not come to that point at all. I wanted to clarify the greenhouse part. Let me come to that so-called thermostat hypothesis.

I will make just a brief statement based on my testimony. The first is our paper's central hypothesis, as yet unproved, is that a possible unstable super greenhouse effect which we found to occur in regions where maximum SST's and deep convection occur together would be moderated by increased cloudiness resulting from the deep convection.

We say this because we have observed that increased ice clouds significantly reduce the solar energy incident on the equatorial ocean during the El Nino warming. El Nino, as many of you may know, is a natural phenomenon of the coupled ocean atmosphere system during which, once every 2 to 6 years, the equatorial ocean, which has a warm pool of water in the western Pacific Ocean, spreads to the central equatorial Pacific, and Dr. Kevin Trenberth is one of the leading experts on this, and I defer any questions of the El Nino phenomenon to Dr. Trenberth.

Going back to the hypothesis, we hypothesize that this cloud-induced reduction of solar energy should limit maximum SST's to less than 32 degrees Celsius.

Senator GORE. Maximum what?

Dr. RAMANATHAN. I am sorry, sea surface temperature. I used the SST. Now I come to the point.

Senator GORE. We have aviation in this committee also, so let us try not to confuse our acronyms.

Dr. RAMANATHAN. It is not supersonic transport. This thermostat hypothesis, even if it is proved, is valid only for the present climate, and that, too, only for regions of maximum SST's accompanied by deep convection.

We are far away from proving this. A hypothesis, including ours, by definition is a tentative explanation of empirical data. It is possible that alternate hypotheses can be formulated to explain our data. However, I have difficulty in the alternate hypothesis proposed by Dr. Trenberth.

Now, I like to talk about implications to global warming. It is premature to extrapolate from the thermostat hypothesis to the global warming, since we have not even proved it for the present climate.

Now, let me address your question, Mr. Chairman. Let us consider the purely hypothetical situation that this hypothesis also applies in the greenhouse rich atmosphere. First, even if it is valid globally it will have minimal impact on global warming estimates since the mean temperature of the ocean is less than the maximum sea surface temperature by about 10 to 15 degrees Celsius.

If, on the other hand, it is valid regionally, such as the equatorial Pacific Ocean with deep convection, in my view—this is purely opinion, and a hypothetical situation—it may only exacerbate the global warming problem, because it is well known from work such as Dr. Lindzen and several others, the sea surface temperature gradient is one of the controlling parameters for the temperature of the atmosphere.

So, that if the warmest waters do not respond but the rest of the oceans catch up to this, the horizontal gradients in the sea surface temperature would be altered, and it is in this context I said in my paper—I wish I had not said any sentence about the global warming—that it is a fact of the problem unanticipated by any of the GCM's.

Senator GORE. So, if the mechanism you discovered, the mechanism you believe your data demonstrates is validated, you would still not expect it to counteract the warming effect of increased greenhouse gas concentrations?

Dr. RAMANATHAN. No, not at all.

Senator GORE. All right. Did you want to comment on this doctor, on his statement there? I know I said I would come to you next, Dr. Lindzen, but I promised him in the opening statement that we would come back to this.

Dr. TRENBERTH. There has been quite a bit of debate in our community about Ramanathan's hypothesis, and indeed your own comment I think reflected some of the impressions that were put forward in the New York Times article and also in Ram's original article which I think left a lot of people with a rather different impression as to exactly what he was saying.

I have less of a problem with the comments he has made here today, and indeed I think in regions of high sea surface temperature the development of strong convective clouds and the resulting shield which blocks out the sun is indeed an effective mechanism for helping to control sea surface temperatures.

One of the points that we have made, however, is that evaporation—surface evaporation and the surface winds—is probably a more important controller of sea surface temperatures in our current climate, and the comment that Ram made a short time ago about the relationship of the regions of strong convection over the oceans and regions of high sea surface temperatures is not always a very clear one.

There are certainly counterexamples where there are high sea surface temperatures where strong convection does not occur, and also, as he mentions, the regions of strong convection is very much dependent on other things, including the proximity of land as well as the sea surface temperature gradients, the contrast in temperature at the surface, and also the atmospheric dynamics. Because if the sea surface temperatures were warm everywhere, you still can only have upward motion in some areas, because there has to be compensating downward motion in other areas.

The other point I would make with regard to this hypothesis is that the process is really not local because of the involvement of the atmospheric motions, and therefore one really needs to get involved with the whole process of climate modeling.

Senator GORE. I would appreciate your forbearance just another moment, Dr. Lindzen. I wanted to try to pin this down. Let me again try to put this in layman's language so that I can have some hope of understanding you.

What you believe you found out is that in tropical oceans there is the formation of clouds which have a convective mechanism that produces these large, anvil shapes high enough in the troposphere such that there is a lot of ice that spreads out over a wide area.



And at the tops of those anvils a lot of the shortwave radiation coming in from the sun is reflected, and the sea surface underneath those anvil-shaped clouds is cooled as a result. Correct?

Now, you were pained at the impression that some got from the overall presentation of your study only to the extent that you did not mean to imply that this was a global phenomenon but was instead limited to the areas in the tropics and underneath those anvil-shaped clouds which you studied. Correct?

Dr. RAMANATHAN. Yes.

Senator GORE. Now, Dr. Trenberth, I will come back to you. Dr. Trenberth goes a step further and says, what goes up must come down. And because you did not set out to study the other side of this convective system, where Dr. Trenberth speculates that when the convecting air comes back down there will be, if I understand Dr. Trenberth's work correctly, less cloud cover in those areas because of the downflow, more shortwave radiation hitting the sea surface, and even at those latitudes, and no overall change in the sea surface temperature. Are you saying that?

Dr. TRENBERTH. Almost. In the atmosphere, at least, there is a very strong compensation between the two regions, and if you are looking down from a satellite there is a very strong compensation between what you are actually seeing from a satellite, but right at the surface the ocean dynamics has to get involved. That is much more ponderous, so that ocean currents cannot move heat around as effectively as the atmosphere, so there can be a net effect on the sea surface temperature within the ocean by blocking the sun in one region and opening up another region.

Dr. RAMANATHAN. In fact, Mr. Chairman, we do see that compensation in the satellite data, so I am not disputing that at all.

Dr. ROSSOW. If I might bring in one other form of data——

Dr. RAMANATHAN. Let me just—I would like to finish this. He is absolutely right about that. There is compensation in other regions. I have some dramatic satellite pictures which show the compensation. I may just like to add one factor. You said in the warm pool locally clouds form. it is also important to recognize that when you heat a part of the ocean you set up temperature gradients so the air moves into the warm region, so the large-scale dynamics was a principal component in our analysis.

Senator GORE. I see.

Dr. RAMANATHAN. And the reason is that it leads to a large buildup of the water vapor over the warm region. This was the so-called super greenhouse effect we found. It is not to be blamed directly on the temperature. It is a cooperation between the warm ocean and the low level bringing the moisture, and that part of the theory, I think Lindzen may want to correct me if I am wrong. The first time I have seen that was in his paper.

So, the water vapor increase is a critical component, and I have been involved in an argument with Professor Lindzen that we find the trapping by the water vapor to be maximum over the regions of convection, but he has an effective argument. He says the anomalous excess trapped energy can be moved away by the dynamics. Maybe, but still you cannot ignore the fact that, at least locally over the region of convection, I do not see this drying effect. If the

drying effect was large to compensate the other large-scale dynamics, we should have seen it.

Senator GORE. OK. We are jumping ahead of ourselves here.

Dr. Rossow, you wanted to make a point, but I told the doctor—I put him off so many times now in this exchange, I want to give you a chance.

Dr. LINDZEN. OK. I really do not have a great deal to say on this, but it is a problem a lot of us have with Ramanathan's definition of greenhouse potential as a local parameter. After all, if you have a column of air, you have a heat flux in from the bottom from the surface radiating, you have flux out the top, but you also have heat fluxes in and out the sides. If you did not have such sideways heat flux, the pole to equator temperature difference would more than twice what it is today. So, this is a very important thing. And Ram's measure just looks at what comes out the top, minus what comes in the bottom and scales it a certain way.

Now, Al Arking could probably speak to this more, but the point is, in order to interpret this, you somehow had to freeze up something and, I believe, what you did was freeze up the temperature profile. Now, in point of fact, in the atmosphere, in order to make the whole thing consistent, what comes out the sides, what comes in the bottom, what goes out the top, all to jibe, you have to allow the profile to change a little and if the profile changes a little, it can upset quite a few of Ramanathan's results.

Al Arking did a calculation wherein, instead of allowing water vapor to change, he used Ramanathan's definition, but used standard atmosphere temperature profiles, corresponding different temperatures. For the region below 300 degrees Kelvin, he gets the same slope for the change of Ramanathan's so-called greenhouse parameter, without any change in water vapor.

Dr. ARKING. Not the same, about one-half.

Dr. LINDZEN. I said for less than 300 degrees.

Dr. ARKING. OK. Well, correct. I could not compare exactly, because the slope that was shown in Dr. Ramanathan's paper includes what happens at the very end, where it gets much warmer. And, so, his slope is influenced by what happens at the high end.

Dr. LINDZEN. Look at the distribution of these dots.

[Dr. Lindzen handed the documents to Dr. Arking.]

Dr. ARKING. Well, yes. This is not the same slope I am talking about.

Dr. RAMANATHAN. That is right.

Senator GORE. Dr. Ramanathan, do you want to respond?

Dr. RAMANATHAN. Yes. First of all, I think the slope they are talking about is a rate of increase of the trapping with sea surface temperature, and we estimated that slope after removing the upper end, and even after removing the large values there is an enormous rise. If we had included it, it would have been much, much larger than anything computed by models.

Senator GORE. Let me shift gears now. We have heard about convection, and I want to see if I understand what you are saying, Dr. Lindzen, at the heart of the argument that you have injected into this debate.

First of all, how would you define "convection"? When the temperature of the sea surface increases, the more water molecules escape as vapor into the atmosphere. And because these water molecules are hot, they rise, as there is a tendency for hot things to rise. The water vapor rises up to where it is cooled. Correct? All right.



Now, what you are saying essentially, Dr. Lindzen, as I understand it, is that when the sea surface temperature increases due to greenhouse gases, you do not dispute, at all, the point that increasing carbon dioxide, methane, chlorofluorocarbons will cause an increase in temperature. It is just that you think it is a smaller increase in temperature. And you say that when that increase in temperature takes place, more water vapor will go into the boundary layer, the first 2 kilometers of the atmosphere. You then suggest that there may well be a convective mechanism by which the water vapor rises through the cloud column and detrains when it gets to the cooler, higher altitudes. This then results in an overall decrease in the amount of water vapor at those altitudes, even with larger increases in water vapor at the lower altitudes, making for an increase in the total column of water vapor. But because there is more water vapor at lower altitudes, and less at higher altitudes, the overall effect of the Lindzen mechanism is cooling. Have I stated it correctly?

Dr. LINDZEN. I have to say, that is about the longest sentence I have even heard as a academic. [Laughter.]

Senator GORE. Well, you will just have to forgive me. That is something the Senate is well known for.

Dr. LINDZEN. I see.

Senator GORE. But aside from the length of the sentence, is it an accurate sentence?

Dr. LINDZEN. Not quite, as best I can track it. First, I must say, the subject is one that is—you should excuse the expression—in flux and so, for example, at this point, I am much more in agreement with Alan Betts than with my original proposition, but let me get to the point of this and it is the important and it has nothing to do with any theory.

Senator GORE. But I would like you to correct my sentence, if you could, because I want to understand what you are saying.

Dr. LINDZEN. OK. What I am trying to say is, the processes whereby the surface gets moisture into the lowest 2 kilometers is very different from the process by which it gets moisture into the region above. The lowest part is separated from the region above by something called an inversion. There is literally a cap to that boundary layer that tends to isolate it from the region above.

The region above is penetrated by these tall towers. Now, the interesting thing about these tall towers—and that is the reason I am coming over to Alan's view—if you just had these tall tower rising and detraining water vapor, the upper troposphere would be bone dry. You absolutely have to detrain liquid water and ice that would be carried by it, and it is that that supplies water vapor to the upper troposphere.

Senator GORE. Now say that again.

Dr. LINDZEN. OK. You have to have these towers. These towers go up. As they cool, water condenses, and it is perfectly possible in principle that this condensed water just forms rain and, as a result, all you would be left with is saturated water vapor.

And what we are saying is, when we calculate the supply of moisture to the upper troposphere—just of saturated water vapor, it is not enough to maintain any relative humidity at all. You would go down to 2 to 5 percent. You observe about 20 percent. We are saying, to maintain the observed relative humidity, you not only have to detrain water vapor, you have to detrain ice in forms which can be carried by the air and continuously reevaporate into the environment, rather than falling as precipitation.

My point is, we do not know what determines how much comes out as ice, how much comes out of water, and how much rains.

Senator GORE. OK. But let me come back to my effort to understand what you are saying. Leaving aside, for the moment, whether the moisture is in the form of ice or rain, or water vapor, the Lindzen mechanism, if I can call it that, describes a possible effect by which the increasing amounts of water vapor escaping from the sea surface create a more powerful convective column. This results in water, in its various forms, being driven to the cooler altitudes and then descending, along with other water vapor that was already up there. Am I getting that wrong?

Dr. LINDZEN. I think you are touching on things that may be right or wrong. We do not know.

Senator GORE. No. But that is what you are saying, is it not?

Dr. LINDZEN. No, no. That is not what I am saying. What I am saying is, we simply do not have a handle on whether clouds in a warmer environment will produce more ice crystals or less. We are suggesting that it is entirely plausible that in a warmer climate you will produce less ice and if you produce less ice, you will have a smaller source of water vapor aloft and you will, therefore, have a negative feedback.

Senator GORE. Well, let me ask a more specific question, because I had thought that what you were saying is that this mechanism will cause a drying of the upper troposphere.

Dr. LINDZEN. I am saying the subsidence does produce drying, but you have a balance between the source of moisture there and the drying due to subsidence.

Senator GORE. OK now, but wait a minute. Just hold on a second. The Lindzen mechanism, if it is proven to be correct, will produce a drying of the upper troposphere. Correct? Right or wrong?

Dr. LINDZEN. This has been hypothesized by us.

Senator GORE. Us being?

Dr. LINDZEN. Myself, student De Zheng Sun, others, that indeed, a warmer surface may very well lead to a reduced humidity aloft.

Senator GORE. Well, just hold on a second. I want to pin this down, because I want to make sure that I understand it. This is extremely important. It is extremely important. The Lindzen mechanism would, if correct, produce a drying of the upper troposphere. Correct?

Dr. LINDZEN. Under increased surface warming, integrated over the globe. Yes.

Senator GORE. If the surface warms, would you agree that it would produce drying in the upper troposphere?

Dr. LINDZEN. You know, I do not want to, Senator, get into the bind of treating one-tenth of 1 degree the same as I treat 5 degrees.



Senator GORE. OK. If the surface warms one-tenth of 1 degree, there will be extra water vapor, correct?

Dr. LINDZEN. In the surface.

Senator GORE. All right. If the surface warms, the Lindzen mechanism would produce a drying of the upper troposphere. Correct.

Dr. LINDZEN. Yes.

Senator GORE. OK. Now, do we have any evidence that that is, in fact, occurring?

Dr. LINDZEN. The answer is, "Yes."

Senator GORE. OK. What is it?

Dr. LINDZEN. OK. There is one, and all the evidence on this, on either side, is highly controversial.

Senator GORE. Well, before you disparage other people's evidence, could you give——

Dr. LINDZEN. No, no. But let me present this, because I am not disparaging others. I am disparaging my own. I am saying that there is a phenomenon that has been observed by Wallace Broker and others, in the reconstruction of the climate 18,000 years ago, in the midst of the last glaciation, and this is a remarkable phenomenon, whereby their measurements show the surface——

Senator GORE. Excuse me. Excuse me, Dr. Lindzen. Just to keep this thing from flying off the edges because of its complexity, rather than looking at 18,000 years ago, do we have any evidence, observational evidence, of the climate system today wherein there is drying in the upper troposphere?

Dr. LINDZEN. We have no evidence on either side for today. The virtue of 18,000 years ago is we know it was a long-term average and that is not available to us today.

Senator GORE. OK. Now, does anybody else have evidence on this point? Dr. Betts.

Dr. BETTS. Well, I would like to make some comments. Part of the confusion of the present discussion is that, if I understood Dr. Lindzen correctly, he has basically withdrawn the original "Lindzen hypothesis" you are referring to, which was that the primary source of water vapor at high levels was from air just saturated over ice—because he has recognized correctly that you cannot explain the present water balance in the upper troposphere without large injections of ice. The original argument that was presented a year or so ago, was based on these cumulonimbus towers that you mentioned going to colder temperatures, where what is called the saturation vapor pressure of water over ice is much lower. And that was the argument for those towers injecting less water if they go higher.

Senator GORE. Now, say that again. I am sorry, but that is one of the ways I can understand this.

Dr. BETTS. Let me back up a little bit further and say that if the ocean's surface temperature warms, the equilibrium near the ocean surface shifts to warmer and moister air as a result of increased evaporation, increased surface temperature, and a complex balance of processes on an ocean basin scale. As a result of that shift, the air that rises from near the surface and forms these thunderstorms in the tropics over the warm waters, will have higher outflow levels.

If the stratosphere cools, then that outflow equilibrium temperature can be colder and the amount of water vapor at the colder temperatures goes down rapidly with decreasing temperature. So, if these towers did not inject ice into the upper troposphere, the air that they would inject would have had less water vapor in it, because it would be coming out higher, and there are some arguments that because it was higher, it would be also be colder, because we expect the stratosphere to be cooler in these conditions.

However, the majority of the water at the highest levels that is put into the atmosphere by these deep thunderstorms is in the form of ice, and the amount that we believe is put in in the form of ice is also consistent qualitatively with the relative humidity, the 20 or 30 percent that we observe in the upper atmosphere from, say, 12 or 13 kilometers, down to about 6 kilometers. Dr. Lindzen says he had now recognized that point, and the discussion now then centers back where we were earlier. It is what controls the equilibrium structure and whether that will shift.

Senator GORE. OK. Well, hold on just a second. Are you withdrawing the original Lindzen hypothesis?

Dr. LINDZEN. Oh, yes.

Senator GORE. Oh, you are. OK.

Dr. LINDZEN. Yes.

Senator GORE. All right. Now, I just want to clarify that for the record. I want to underline it. The original Lindzen hypothesis is formally, here today, at 11:45 a.m., withdrawn. All right.

Dr. LINDZEN. Well, in fact, it was much earlier that we withdrew it. There is a paper——

Senator GORE. Excuse me for not noticing it earlier.

Dr. LINDZEN. OK.

Dr. ROSSOW. I might mention a few pieces of evidence—at least one and three-quarter pieces and I will tell you why I say that. There is a data set from the SAGE instrument on a satellite, which has been looked at in two ways. This instrument measures water vapor outside of clouds above about the middle of the atmosphere, as we refer to it—say, 7 kilometers altitude and above. The data indicates two things as reported in a paper by Dr. David Rind.

One is that the seasonal progression of water vapor changes is opposite what you might infer from this hypothesis, in that the warmer hemisphere is moister aloft.

The other thing that is more interesting is that the data indicates that if you look at the spatial pattern of the water vapor, the lower stratosphere and upper troposphere have more water vapor in the areas where the convection is occurring. So, it is a very suggestive relationship that the convection is actually injecting water at those levels.

Now, the other "three-quarters" piece of evidence, if you will, is that some efforts have begun to try to look at the same thing using conventional data instead of using satellite data. These are attempts to measure water vapor in the upper atmosphere and compare the water vapor amount in warm years versus cold years. As I understand it, the initial results seems to suggest the opposite result; namely, that the warmer years were a little drier. However, when you show that to people who are experts in that type of instrumentation, they usually tell you that that is consistent with the errors those instruments make.



So, that is a partial piece of evidence in the sense that it points out that some of our sources of data need improvement.

For what it is worth, I should also mention what the climate models do. There are three models that I know of that include the particular processes that Dr. Lindzen has proposed are important to the story. When you isolate in those models, the effect of the convection on upper atmospheric water vapor, it shows drying.

However, there are other processes in those models and the net effect always seems to be a moistening.

Senator GORE. A paper, a letter to Nature dated February 7, 1991, by Rind and others states that new satellite-generated water vapor data shows that increased convection leads to increased water vapor above 500 millibars. What is 500 millibars?

Mr. ROSSOW. About 5 kilometers. That is the data I was referring to.

Senator GORE. 5, 5.5 kilometers. That increased water vapor above 5.5 kilometers is in approximate quantitative agreement with results from current climate models.

The same conclusion is reached by comparing the tropical, western, and eastern Pacific regions. Thus, we conclude that the water vapor feedback is not overestimated in models and should amplify the climate response to increase trace gas concentrations.

It seems to me that this is an extremely important point because of all of the uncertainties raised about the operation of clouds and water vapor in global climate models, the one which has served to generate the most doubt that we have something to worry about has been what I refer to as the Lindzen mechanism, whereby increased convection dries the upper troposphere.

Now we have not only the author of the Lindzen hypothesis withdrawing the original hypothesis——

Dr. LINDZEN. Excuse me, sir.

Senator GORE. I will give you a chance to respond.

But some evidence of increased water vapor associated with increased convection. Dr. Lindzen.

Dr. LINDZEN. Senator, I mean, since I do not quite know what is meant by the Lindzen hypothesis, this business of naming it, let me try and clarify.

There was a very specific way in which clouds that only detrain saturated water would, in fact, dry subject to warming. That specific mechanism, I do retract. Not only for the reason that Alan Betts mentioned, but for another reason which is technical. And we can discuss that.

But that does not mean that I have seen any evidence for increasing upper level water vapor rather than decreasing subject to a warmer surface. In other words, I still believe the feedback can be negative. And I do believe there is evidence.

As concerns the paper by Rind, et al. in Nature, I would point out and others have pointed out, that the water vapor distribution in the upper troposphere is a function of the circulation as well as the sources and sinks.

And what Rind, et al. did was compare one-half of the circulation with the other and conclude that it was dryer where air descends

and moister where air rises. And nobody, nobody, would contest that at all.

Our point simply is that seasons are not a surrogate for climate.

Senator GORE. The reason, I mean, is that this is a subject that is extremely complex. And many of the points that I made in the discussion seem at times to be very arcane.

But the relationship between the formation of public policy on the one hand and the understanding of scientific phenomena as described by researchers on the other hand, is itself in need of a good deal of study.

What my own observations of that relationship indicate to me is that loud and persistent doubts are forcibly interjected into a scientific debate in ways that tend to distract public policymakers from recognizing a near consensus when it is present within the scientific community.

The near consensus as evidenced in the IPCC report and in the scientific community generally is that the odds seem to be heavily in favor of water vapor and clouds serving overall as a magnifying phenomena, increasing the warming potential of increased concentrations of carbon dioxide and other greenhouse gases.

In opposition to that near consensus we have also heard about numerous complex phenomena which, as in the instance of the $SO_2$ phenomenon that Dr. Charlson described, almost certainly overwhelmed by warming as are greenhouse gases continue to increase in concentration.

We have the convective mechanism explored by Dr. Ramanathan and his colleagues in tropical oceans, which again, they feel is certain to be overwhelmed by the warming trend associated with increased concentrations of greenhouse gases.

But in addition to these debates within the near consensus, there has been a persistent challenge posed by Dr. Lindzen, which as I understand it, rests upon a hypothesis which has now been, at least in part, withdrawn.

But as a followup to the exchange earlier, Dr. Lindzen now asserts that he continues to have the feeling that the role of water vapor and clouds is likely to be a negative, instead of a positive, a feedback to warming. Correct?

Dr. LINDZEN. That is correct.

Senator GORE. Now what is your feeling based on this time? Or is it the same? Am I being unfair?

Dr. LINDZEN. You are, of course, being unfair.

Senator GORE. Is it the same hypothesis?

Dr. LINDZEN. No. The point I have been trying to make and that is made in the testimony is that the basis being at the most objective, saying that water vapor does anything, increases, decreases above 2 or 3 kilometers is not present in any existing model. Unless we know that, we have no basis for calculating the response to increasing $CO_2$.

The second thing I am saying is, we know from the data concerning temperature change over the last century, the last millions and billions of years, that the more extreme model predictions are out of line and must have some exaggeration in them of which this is the most likely because it is the biggest.



Senator GORE. Let me pursue this. I apologize to the other participants here. I know some of you want to jump in on this.

But the question of burden of proof, it seems to me, is quite relevant here. It is one thing for you to say that those who feel that water vapor is going to be a positive feedback, water vapor and clouds taken together would be a positive feedback to warming. It is quite another thing to say that you have some basis for believing that water vapor is likely to be a negative feedback to warming.

Now it is also one thing to say that the models are less than perfect, a point on which I believe everyone agrees. But it is another thing to say that observational evidence from atmospheric processes now subject to observation, lends some support to your hypothesis.

Dr. LINDZEN. Excuse me, I think you are mixing a number of things, Senator.

The first statement is where does the burden of proof lie. And it seems to me that if there is no basis for presently stating that the models can calculate the upper level water vapor, there is no basis for saying anything.

Now on problems where one cannot say anything, it is very difficult to know how society should respond.

The second thing is, I am a little bit unclear as to which data you were referring to, but I must say in connection with Rind's paper, in connection with Ram's paper, with Ramanathan, with Raval, that I do not see in that any answer to what design of the water vapor feedback is.

Senator GORE. Does it cause you, in continuing to assert your belief that it is likely to be a negative feedback, any concern that your original hypothesis was wrong?

Dr. LINDZEN. It does not for a very simple reason. That is how science is done. And if I find something I have done is wrong, I would like to be the first one to know about it.

And that happened in this case. That in no way alters the fact that I see no basis for the positive water vapor feedback, which is essential to every model prediction.

Senator GORE. OK. But what is the basis for your feeling that it is likely to be a negative feedback? That is what I am trying to get at.

Dr. LINDZEN. Very simple. Very simple. It is that as far as we can tell every model predicting an excess of 2 degrees is predicting more than we have already seen.

And as a result it seems to me that all models currently predicting these numbers are excessive.

Senator GORE. OK. But, again, that is a negative point about the other side.

Dr. ROSSOW.

Dr. ROSSOW. I would just say that I do not understand Dr. Lindzen's remark. It depends on how you compare the models to the available temperature record.

Most models have been run in a form where they simply change the greenhouse gases suddenly and then look at the new equilibrium. If you look at the change in temperature from old to new equilibrium and draw a straight line between those two, you may or

may not conclude that they disagree with the last 100 years or so of temperature records.

But there is another way to run a model and that is to start it from some moment in time and change the greenhouse gases and other things you know about slowly as they actually change. When you do that, some models do resemble the temperature record.

However, there are two things to say about that immediately. One is that that is not proof, it is just circumstantial evidence, but it is not the strong negative that Dr. Lindzen has suggested.

Second, there are some things going on in the climate, particularly the changes in aerosol that we are not sure we know about. So, our estimate of the forcing that model should get is therefore subject to error.

Also, the agreement or disagreement with the current record may also be subject to that same error. But it is not true that all models disagree in a strong, quantitative sense. There are some that disagree, some that agree within the spread of results that we continue to discuss.

In fact, most models taken from the least sensitive to the most sensitive predict about the same transient response for the first few decades because in that time scale the ocean temperature has very little time to change. And therefore, most of the feedbacks have not yet come into play.

Senator GORE. Dr. Betts, Dr. Cess, and Dr. Arking have my attention.

Dr. Betts, it may be that Dr. Cess, since he is an expert on these models, might go first. I will just call upon you then in that order.

Dr. BETTS. I think before we move into discussing the whole range of climate change going back a few billion years, which involves an enormous range of other issues, just let me say we are putting a perturbation into the atmosphere on a time scale that is far shorter than the time scales of the geological record. And one has to be very careful about drawing inferences from the past, even the past Ice Age, with its time scales, let alone longer geological periods. But we can come to that point. That is another subject.

I would like to discuss the crucial issue that Professor Lindzen is still raising doubts about. That is, How much do we understand about the coupling between temperature and water vapor? You might say this is an arcane subject to discuss in this forum, but I will just try to say a little bit about it very briefly.

We do understand quite a lot about the water vapor equilibrium in the tropics, which is the primary issue in this discussion. Even though there is a great deal about it from an observational point of view that is not yet known, we have fragments of observations. And they are consistent with our conceptual models.

The basic issue as to what controls the equilibrium in the upper troposphere in the tropics is how long air has sunk, and at what speed, since it was last saturated. Because if you imagine air flowing out of a thunderstorm anvil system, at some point those ice crystals evaporate and the air is left saturated close to temperature equilibrium. And then the only process by which it can sink is a long time scale process. It is the radiative cooling of that air.



That radiative cooling is a function of its water vapor. It is a function of its temperature structure. But it is something that we can calculate.

How unsaturated it becomes, how dry it becomes, can be calculated directly from its rate of cooling and two well-known thermodynamic curves in the atmosphere. One is the temperature structure that is characteristic of the tropics, which is the temperature of parcels as they rise condensing and precipitating their water. And the other is the change of temperature with pressure at constant mixing ratio as air temperature cools.

Let me just elaborate one moment here. There are two processes that are going on. One is, air is cooling. It starts out saturated and it sinks. If air sinks, which it does because it is cooling, it becomes less saturated and dryer.

While that is happening, though, the level at which it is saturated is also changing, because of the radiative process. And both these effects can be calculated.

The sinking motion characteristically exceeds the rate at which its saturation level changes, so you can actually calculate the rate at which it dries out from the rate at which it cools and sinks in the upper troposphere. Above the middle atmosphere, around 5 or 6 kilometers, this "drying rate" decreases from about 15 millibars per day to about 10 millibars per day at high levels.

I am not sure what the value is at the very highest levels, but if we confine ourselves to say 250 to about 500 millibars, which is about 6 kilometers to about 11 or 12 kilometers, then the atmosphere we have today is consistent with air sinking for only about 5 or 6 days with this process going on that makes it steadily drier. We see that in air which sinks back into the boundary layer, and we know that the air at any given level in the atmosphere has not sunk from very high levels in the atmosphere but has only sunk about a few kilometers—perhaps 100 millibars—for typical periods of the order of 5 or 6 days.

Put that argument aside for one moment. The coupling of temperature and water vapor in the atmosphere, with which we started out this discussion, is such that if the atmosphere warms, then unless the relative humidity—which is this measure of the dryness of the air that we characteristically use even at the surface—unless that decreases significantly, then there is a positive water vapor feedback.

So, the burden of proof here is not simply whether relative humidity changes by a few percent. In fact, relative humidity has to decrease from about 30 to 15 percent in the upper troposphere, roughly one-half, in order that the water vapor feedback shall be negative. If it only changes by a few percent we are simply arguing about how large a positive effect it is.

Senator GORE. I see.

Dr. BETTS. The final point in this argument is that the evidence that we do have from our conceptual models of the whole coupled ocean-atmosphere system in the tropics is that if anything the relative humidity will increase slightly in the event of global warming, and the reason for this is that there are two processes at work. One is the radiative cooling rate, which we would expect to increase,

and the other is the stability of the atmosphere, which if the atmosphere warms we also expect to increase.

They depend on different physical processes in the gross average for the tropics, and the increase of the stability is slightly greater than the increase of the net cooling of the atmosphere; and so my assessment is that the evidence we do have is that the water vapor feedback is likely to be positive. Thus, although it is uncertain within a certain range, what evidence we have from conceptual models is that the relative humidity will not decrease in the tropical upper atmosphere.

I realize that was a long-winded response.

Senator GORE. OK, I think I understand that. I probably do not, but you stated it so lucidly that it gave me the impression that I understood it. [Laughter.]

Part of what I think I understood was that as the total air column warms, as the sea surface temperature warms, the total air column warms.

Dr. BETTS. Yes.

Senator GORE. Taken together. Correct?

Dr. BETTS. Yes. The whole tropics warms if the mean tropical temperatures, particularly over the warm regions, warms.

Senator GORE. Anybody disagree with that?

[No response.]

Senator GORE. OK. If the total air column warms, then the absorption mixing ratio—is that what you call it?

Dr. BETTS. The saturation mixing ratio.

Senator GORE. The saturation mixing ratio increases. That is yes, so let me state it another way. The total moisture carrying capacity of the air column increases. Correct?

Dr. BETTS. Yes.

Senator GORE. All right. Anybody disagree with that?

[No response.]

Senator GORE. That increase, the rate of that increase is quantifiable?

Dr. BETTS. Yes.

Senator GORE. Now, the other mechanism is the convection rate which is also quantifiable?

Dr. BETTS. It is part of the coupled system as a whole, yes, and so we do know that it is related to, ultimately, the radiative cooling of the atmosphere, among other things.

Senator GORE. Now, what you are saying is that based upon known facts about the atmosphere, the rate at which the saturation mixing ratio increases has more power over the total amount of moisture in the upper troposphere than any increase in the convection?

Dr. BETTS. That is a known large quantifiable effect. The injection of all the water and ice into the atmosphere is by convective clouds and anvil clouds, and the point at which the clouds evaporate, they—well, it is not quite true of the ice clouds, but essentially the quantifiable threshold we have is on the saturation mixing ratio, which goes up with temperature. The arguments here about the greenhouse effect——

Senator GORE. Wait a minute. Wait a minute.

Dr. BETTS [continuing]. Depend on the absolute amount of water.



Senator GORE. Now, the absolute mixing ratio—let me state it and then you correct it. It is easier that way.

The absolute mixing ratio is——

Dr. BETTS. Relative humidity times saturation mixing ratio.

Senator GORE. OK. The absolute mixing ratio is the saturation mixing ratio plus the total amount of water vapor?

Dr. BETTS. No.

Senator GORE. Times the total amount of humidity.

Dr. ROSSOW. You said it right. The saturation mixing ratio is the carrying capacity.

Senator GORE. Yes.

Dr. ROSSOW. And the absolute mixing ratio is how much is actually there.

Senator GORE. It is the combination of the carrying capacity and how much is actually there?

Dr. ROSSOW. No, it is just how much is there.

Senator GORE. OK. All right.

Dr. ROSSOW. So, when we are telling you a relative humidity value, we are telling you how full the bucket is.

Senator GORE. So, what you are saying is that the effect of warming the air column, on the saturation mixing ratio, has much more of an impact on the absolute mixing ratio than does convective forces, unless you have a dramatic decrease in relative humidity?

Dr. BETTS. No. The relative humidity here is a consequence, and there has to be dramatic changes in the dynamics of the whole process in order for the relative humidity, which we also understand in the present atmosphere to change dramatically from its present 20 to 30 percent, and so far no evidence has been presented for that.

Dr. ROSSOW. I can give an example of two models, one that includes the convective drying process and one that does not. When you warm those two models, in the case of the model with the drying mechanism included, the convection acts as a drying agent but the other dynamic motions end up moistening the upper levels more.

Senator GORE. I see.

Dr. ROSSOW. In the model where the convection does not have that mechanism, it acts as a moistening agent and those other dynamic motions act as drying agents but moistening wins in both cases. We do not know which is the right story in the way that Dr. Betts posed it in terms of which way the relative humidity will change, but what we are saying is that the relative humidity has to decrease an awful lot to change its radiative effect to a negative feedback.

Senator GORE. I believe you said 15 to 20 percent.

Dr. BETTS. It has to roughly halve in the upper troposphere.

Senator GORE. Roughly half?

Dr. BETTS. Half, yes.

Senator GORE. I want to give Dr. Lindzen a chance to respond to this. As I understand it, and I want to be fair in stating this, you are saying that there is a basic conceptual flaw in Lindzen's hypothesis.

Dr. LINDZEN. My suggestion—let Alan speak to that.

Dr. BETTS. Let me say I strongly disagree. I think the burden of proof is shifting much more heavily here, because not only does it have to be a large decrease, we have to also devise mechanisms by which such a large decrease could become possible, and from what we know, again, of the equilibrium balance, it requires some rather dramatic changes in time scales of the dynamics of the tropical atmosphere.

Senator GORE. Well, Dr. Lindzen, is your continuing feeling that water vapor is likely to be a negative feedback still based on the feeling that the upper troposphere will probably dry out?

Dr. LINDZEN. Well, they are the same statements.

Senator GORE. But it is not a generalized feeling, it is tied to a feeling that it will come from a drying of the upper troposphere?

Dr. LINDZEN. Senator, Alan was——

Senator GORE. But if you could answer that point, it is important.

Dr. LINDZEN. Yes, yes. That is fair. The business of the saturation changing with temperature, that is totally uncontested, but the statement that this has anything to do with the actual water vapor is equivalent to the statement that if you give me a 1-quart tankard and a 1 pint goblet that the 1 quart will always have more liquid in it, regardless of what you pour into it, and that is nonsense.

So, the question really reverts to the source, and the question that I do not think Alan is addressing is, why in the world would one expect the amount of ice detrained by a cloud to increase when it is warmer?

Senator GORE. Do you want to respond to that?

Dr. BETTS. Well, that particular question, we do not know quantitatively enough at the present the relationship between the ice and the saturation mixing ratio, so quantitatively we cannot answer that question.

In the overall balance of the water in the upper troposphere both the water vapor that is detrained, to use the jargon, and the ice, are important. The ice is most important at the highest level. They are both important at middle levels—well, let us say around 10 kilometers.

Whether or not the ice increases with temperature—and there is some weak expectation it might, because the amount of water in the clouds increases with temperature since the amount flowing through the bases of the clouds goes up with temperature. But that is a question we do not know the answer to.

It still requires some major changes to change the relative humidity, which is controlled by sinking processes in the atmosphere, which are themselves radiatively driven and for which we can calculate how dry air will be after it has sunk for so many days. The changes that are required to produce negative water vapor feedback, as I mentioned earlier, are something like a halving of the relative humidity.

Dr. LINDZEN. Excuse me. It has to be proportional to temperature. Where does the absolute number come from?

Dr. BETTS. You are correct, that is based on a 2-degree sea surface temperature rise. That is correct. So, it is all proportional. The 2-degree sea surface temperature rise in the tropics is a characteristic somewhat lower end of the figures that have been quoted for a double $CO_2$ rise.



Senator GORE. I know that others want to make a few points here. But just to pursue this for a moment, you have said, Dr. Lindzen, that your feeling that this is likely to be a negative feedback, overall, is based on your feeling that the upper troposphere will dry. What I would like to know is, how do you now hypothesize that that might take place?

Dr. LINDZEN. Oh, there is no difficulty if you are in the realm of hypothesis. In the realm of hypothesis, one simply has to have that when it is warmer clouds produce less ice relative to water and saturated water vapor, and when it is colder they produce more ice and one will have a negative feedback.

So, stated that way, there is a certain plausibility to coldness being associated with more ice. No one would claim we know this. What I have said, I repeat, is for all the models the presence of strong positive water vapor feedback is essential to their producing scenarios of large warming, and we can safely say that therefore all predictions of that sort of warming are based on something we simply do not know.

Senator GORE. Now, other than 18,000 years ago, do you have any evidence to support this hypothesis?

Dr. LINDZEN. At this stage, it would be very difficult to have anything comparable to what we had 18,000 years ago, because that represents a long-term average of the structure of the atmosphere.

Senator GORE. Well, of course, average is not the same as the actual experience. But is there any evidence at all that you can offer us in support of your hypothesis?

Dr. LINDZEN. The only evidence I can offer you is that it is in the realm of possibility, which in fact is all the evidence we have for the positive feedback.

Senator GORE. Well, of course.

Dr. Cess.

Dr. CESS. Let me get back to the paper for just a moment, because there is a very important piece of information in there that is generally overlooked, and that is that if the models were totally off the wall as far as mid and upper tropospheric water is concerned to give the kind of changes in relative humidity that Dr. Betts has mentioned, then it would be rather difficult to see or to believe that they would give the proper change in mid and upper tropospheric water vapor as you go through the seasonal cycle.

The important point in that paper is that by using seasonal variability as a test—not a surrogate, not a proxy, but as a test—that particular model did a very good job in producing the seasonal change water vapor in different geographical locations.

Now, having said that, let me go back and just correct a statement you made earlier, when you said that there was a broad consensus that water vapor produces a positive feedback mechanism and clouds produce a positive feedback mechanism.

Senator GORE. I believe I said near consensus.

Dr. CESS. Broad, near, whatever. That is, I believe, true with respect to the water vapor. Dr. Lindzen is a singularity here, I think. As far as clouds are concerned, I do not know anyone brave enough to predict what the sign of cloud feedback would be.

Senator GORE. What I said was, water vapor and clouds taken together. How would you state the prevailing view on that?

Dr. ROSSOW. The same way.

Dr. CESS. The same way.

Dr. ROSSOW. It is the clouds that are the wild card.

Dr. CESS. Yes, and the clouds could—well, let us assume Dick is right on the historical temperature record. It could be the clouds that are producing the feedback, whereas the water vapor is still producing the positive feedback.

Dr. ROSSOW. I might say that there are climate models—again, this is not necessarily proof—but there are climate models which in fact do produce the proper Ice Age-to-current transition temperature.

Dr. RAMANATHAN. The equatorial ocean, I think. I think Lindzen is referring to the equatorial ocean, which does not seem to have changed very much. Again, there is some confusion about it.

Dr. ROSSOW. There also is some confusion about the data on that point, but let me say that in terms of overall climate sensitivity there are models which are consistent with the data when the known forcings are put in. What the situation was before we discovered that the last Ice Age was associated with a change in some of the greenhouse gases was that most of the models could not predict a big enough change, so they were less sensitive, apparently, to the known forcing changes.

Senator GORE. There is also evidence from the ice core records that atmospheric carbon dioxide and global temperatures go up and down together.

Dr. ROSSOW. Yes. My point is, just to clarify the following suggestion, the models with known forcing before the discovery of the greenhouse gas changes associated with Ice Age were less sensitive. They could not produce a big enough change. So, if anything, the problem with the models was the other way around from what Dr. Lindzen suggests. They were underpredicting the changes.

Senator GORE. I see.

Dr. ROSSOW. But once we found out about a new forcing, which was the greenhouse gas changes, there are some models that are now consistent with the Ice Age records in terms of how big their temperature change is, so there is still not really any strong statement that can be made that the current models are overly sensitive. They are not.

Senator GORE. Dr. Arking.

Dr. ARKING. First of all, some clarifying remarks. First of all, the way the community interprets the Lindzen hypothesis, it is the drying of the upper troposphere. The mechanism is what may be in dispute. In that connection I would like to mention that in order to have a significant water vapor feedback you have to be injecting a lot more water vapor into the upper troposphere than otherwise.

For example, if you were to assume that the amount—the absolute amount of mixing ratio of water vapor—did not change in the upper troposphere but only changed in the boundary layer—where everyone admits water has to go up in the boundary layer, what you would find is that the total water vapor goes up significantly when you double the $CO_2$. The total water vapor goes up maybe 5 or 6 percent. But if the upper troposphere remains dry, you have almost a negligible water vapor feedback.



So, it is important in terms of trying to balance between who has the burden of proof, whether the one who says that you have to prove that you do not inject more water, or the one who has to prove that you do inject more water.

I think the question is—and I think Alan Betts recognized this—we do not understand the physics well enough to be able to be sure, and that is why we are grabbing at circumstantial evidence to indicate that it may go one way, perhaps it may go the other way.

Senator GORE. But, this discussion of burden of proof takes place in a real world in which we are in the process of doubling the greenhouse gases in 40 years.

Dr. ARKING. Yes, and that is exactly the point.

Senator GORE. And the discussion here today is of interest to the U.S. Senate, not only to drive our choices about allocating funds in the research budget, but also to formulate our reaction to various proposals to slow down or stop this dramatic human-caused change in the concentration of greenhouse gases.

So, when evidence is presented by the scientific community which leads us to believe that the introduction of these extra greenhouse gases has the potential to cause a catastrophic change in climate, we have to balance that against the assertions by others that that probably will not occur.

Those who say that there is evidence suggesting it will occur have provided not only computer models, but also observational evidence that tends, in their view at least, to support what they are saying.

What I hear on the other side is that there is a potential, or it is in the "realm of possibility," to quote Dr. Lindzen, a moment ago. It is in the realm of possibility that this could be negative instead of positive.

But there is not only no computer model, there is no observational evidence upon which to base that assertion. Now, in weighing these two competing claims, the absence of evidence on the side of those who say it is likely to be negative is quite significant. And since one purpose of the debate is to decide whether or not to address the human activities that are causing this change in greenhouse gas concentrations, it seems to me that there is a rather heavy burden of proof on those who challenge the conclusions of the IPCC and others, who believe that the most likely outcome is that there is a positive feedback to warming.

May I make just one more point on the issue of balance of proof, since you raised this issue, Dr. Lindzen? As I understand the consensus within the scientific community, it is generally agreed that the increased concentrations of $CO_2$ and $CO_2$-like gases rely upon this leveraging mechanism to turn water and its various forms into a magnifier, a positive feedback to climate warming.

But the potential seems to be one that should be taken seriously. And to focus on the question of the burden of proof, bear with me for a moment. All of you are much more familiar than I am with the record from Vostok and the relationship between $CO_2$ and temperature, ill-understood as it is.

I took the liberty of plotting on this graph the increase in the concentration of antropogenically derived $CO_2$. Can you see that there?

Dr. LINDZEN. I am familiar with the curve.

Senator GORE. Over the next 40 years or so, when $CO_2$ is predicted to double, the $CO_2$ curve then line goes up to there.

Dr. ROSSOW. And that is just the $CO_2$.

Senator GORE. No, that is actually, that includes the others.

Dr. ROSSOW. Because the methane also had a similar historic curve.

Senator GORE. Without the $CO_2$, and without other greenhouse gases that imitate $CO_2$'s effects, I think it stops somewhat short of that. For example, now it is at 400 ppmv when you combine all of the greenhouse gases. And it is, what, 360 ppmv with just $CO_2$?

Now the point, Dr. Lindzen, and I want you to open your mind on this question, and I do not mean that pejoratively at all, I am dead serious in asking you this question.



In discussing this point about the burden of proof, is the burden of proof properly placed on those who say that it is probably not all right to do this, if $CO_2$ in the atmosphere, and temperature, have covaried over at least the last 160,000 years? And we are in the process, in one generation, of pushing these concentrations up to 600 parts per million.

What you are saying, and I do not want to be unfair, what you are saying is that it is probably all right to do this?

Dr. LINDZEN. Senator, you have taken the Vostok record, which, by now, by and large, is accepted in the scientific community as having no particular causality, since it appears from whatever we can tell, it is temperature that leads $CO_2$. And deducing, it would seem from this, that $CO_2$ does the opposite—it causes the change.

I do not see how you can see that. We have ample evidence, even that during the medieval optimum, 1,000 years ago, $CO_2$ underwent a marked rise. And as far as we can tell, that is in response to temperature.

Senator GORE. Marked being?

Dr. LINDZEN. It went up to 300-something, according to the cores that they have.

Senator GORE. 300?

Dr. LINDZEN. I do not have the exact number.

Senator GORE. 303, 304, 350, 360?

Dr. LINDZEN. It was about 320, the medieval optimum. The point simply is there is ample evidence that temperature affects $CO_2$. To conclude from that the $CO_2$ affects temperature is a very different question. It is one you may wish to legislate on, but it is not one which a scientist should be convinced by.

Senator GORE. Well, but the point is on the burden of proof.

For example, many scientists said, in response to the paper by Sherwood Rowland and Marion Molina, that it was probably OK to increase the concentrations of chlorine, chlorine monoxide in the atmosphere, by 3oo to 500, and now by almost 600 percent. And yet partly because of the doubts raised within the global community, and because of the coupling of the political system and the scientific debate, the political system waited and did not respond. And the concentrations continued to the point that the risk posed to the global atmosphere, as a result, is now significantly higher than it would have been otherwise.

And to say that the burden of proof in that case was solely to be borne by Rowland and Molina, would have been wrong. Unfortunately they did have to carry that burden. Fortunately, they did so successfully. And this question, these phenomena in question, are even more complex, much more difficult to understand. And yet the consequences could be significantly more catastrophic.

And to say then, that the burden of proof rests solely with those who point to this extreme change in the natural makeup of the global atmosphere, is, I think, wrong.

Dr. ARKING. Senator, could I——

Senator GORE. Dr. Arking.

Dr. ARKING. When I was referring to the burden of proof, being, perhaps, more or less equal, I was referring to the scientific debate. And this is where we have to make a distinction between science and policy.

Because from a scientific point of view, you have to prove something before it is accepted scientifically. And, in fact, the question of consensus is almost irrelevant from a scientific point of view. Because every significant breakthrough in science has come because somebody was willing to depart from the pack, and strike out on his own, and risk his reputation.

Senator GORE. Absolutely.

Dr. ARKING. And to go out and prove something. Every major, significant discovery in science has come about that way.

When it comes to public policy, I agree with you, Senator. One does not simply go back and say you prove it to me scientifically, close to 100 percent; otherwise, I do not believe it. That is not the way policy is done.

And I agree with you. The fact is that there is a significant risk that there will be global warming of the magnitudes, even though we cannot prove it. And perhaps, over the next 5, 10 years, you might see shifting one way or the other—whether it is going to be larger or smaller. And, in fact, the IPCC document was pretty fair in assessing a fairly wide range, from 1.5 to 4.5 degrees, in the doubling.

So, your job is a lot more difficult than ours. From our point of view, we will argue the facts, and we will demand proof of everything as we go along. And we will shift back and forth. But you have to then take the limited information that you get from the scientists and formulate a policy. And I cannot blame you for saying that if there is a risk—it may be only 10 or 20 percent, or maybe 60 or 70 percent, that we will have an unacceptable amount of global warming—that you may have to take steps before we can give you the final answers.

Senator GORE. Well, the problem in a nutshell is that science thrives on uncertainty. And politics is paralyzed by uncertainty. As a consequence, in this dialog, which this roundtable series is designed to promote, it is imperative that politicians, who are elected officials, try to dig beneath the surface to examine the relative magnitude of the uncertainties still present within the scientific debate—both with an eye to eliminating those uncertainties, where possible; but also with an eye to weighing their relative significance in avoiding the paralysis which even a modicum of uncertainty has, in the past, produced within the political system.

It would help in that dialog if there was some mechanism within the scientific community to convey the community's impression of how significant these remaining uncertainties are.

As a nonscientist, I am persuaded that the lack of any supporting evidence for the Lindzen hypothesis, for example, contrasted with the voluminous evidence that seems to suggest that to the contrary, water, in its various forms is likely to be a positive feedback, shifts the burden of proof.

Dr. ROSSOW. Senator, may I just say that we should come back to now what is really the crux. Even if there is a consensus on water vapor—at least at the table—there is another way that the drying or moistening of the upper troposphere would be crucial. That is its effect on the high-level cloudiness. That effect could change the sign of the cloud feedback.



So, the cloud feedback is still the wild card in the story, even if there is some consensus on, say, the vapor phase. Unfortunately, the cloud feedback also depends on that vapor phase and it depends on even a small change in the relative humidity.

So, really, the clouds in the upper atmosphere could amplify anything that vapor is doing and be more important in that sense.

Dr. RAMANATHAN. I am not sure you could say amplify, also.

Dr. ROSSOW. I said could amplify. I did not say I know the sign—could damp, as well.

I think one thing we could say, to echo Dr. Cess, is that there is probably not really a consensus on what the clouds will do—I do not think there is. And this issue which we have discussed for the past hours is, at least, one of many issues that gets involved as soon as you say you have to get the clouds right.

Senator GORE. All right, before recognizing Dr. Trenberth, I did just want to say, for the record, on the Vostok core—and again, I think you said this, Dr. Rossow—that we could not have had such a large change in temperature, without some positive $CO_2$ feedback.

The climate record documents these large temperature and greenhouse gas changes. And the record shows $CO_2$ did change, and that it was a factor and cannot be ignored. Indeed, it is hard to get to the 5-degree rise that the records show if $CO_2$ did not play a forcing role.

And on these and other points that have been passed by in the debate, I will invite further comments for the record. I do not wish to dwell on it at this point.

If you wish to make a very brief comment——

Dr. LINDZEN. You should be aware, as concerns using $CO_2$ to improve modeling of glacial climates and interglacial climates, that the most extensive modeling effort at Princeton University continues to fail to get the cycles—no matter how much $CO_2$ they toss in. And the same is true for the efforts of Michael MacElroy at Harvard. He finds he has to make $CO_2$ changes several times what was observed, in order to get it to dent the climate response.

Senator GORE. OK, Dr. Rossow spoke to that point earlier, as did Dr. Cess. And I would simply refer people back to the record on that point.

Dr. TRENBERTH. I have three short comments: the first one is that in our community climate model at NCAR, that in order to simulate today's observed moisture in the upper and middle troposphere, from 9 to 12 kilometers, we have to have a certain amount of detrainment in the convective parameterization scheme.

Now, you can say that we have to do what is referred to as tuning, in order to get the observed climate correct. But then you can take that particular form of clouds that we produce as today's climate and see what it does under a greenhouse gas scenario. And indeed those clouds produce an increase, a positive feedback effect. And I think that does, indeed, place the burden of proof on Lindzen to say that it is going to operate in the other direction.

The second point I wanted to briefly emphasize was that from the observed record, we have seen about one-half degree Celsius warming. The prediction for doubling is 2 to 5 degrees, roughly. That was the range that was dealt with by the IPCC report. But

they focused on a number which they said was a compromise between the observational record and the model predictions of 2.5 degrees C.; and I think 2 to 3 degrees C. for doubling of carbon dioxide is compatible with the observational record. You do not have to go down to less than 2 degrees, as Lindzen seems to be suggesting.

But then, if you are interpreting the observational record, you also need to be aware that increasing carbon dioxide is not the only thing that has been going on. And the point that Charlson made, indeed, with regard to aerosol is just one of other factors that is going on in the real world, when you are interpreting the real, observational record.

Senator GORE. Yes, Dr. Betts.

Dr. BETTS. I wanted to make a few, brief comments, Mr. Chairman, on this issue. Because I think the real problem that is faced by the political system is even worse, perhaps, than you suggest. Because even though I have spoken, for example, about what we do understand about the water vapor feedback in the Earth's atmosphere, I am well aware of the uncertainties in all the modeling efforts in the whole climate system.

And if you look at the complexity of the system we are dealing with, and look at the dilemma that we are faced with in the next few decades, if we wait a few decades for increased observational certainty—as has been suggested—it may be one or two decades before the record is clear, because of the natural fluctuations in the climate. We will have increased real confidence that we are seeing a greenhouse signal, if we wait. At the same time our models are less than satisfactory, but we hope that they will improve.

We have to recognize that we have to deal with the interaction with the biosphere, and with the oceans. And that is a much bigger modeling problem—to be successful—than just the atmosphere alone. But if we do wait, then the problem of reversing the trends that have already been in place for a few decades becomes much more severe.

So, faced with what the scientific community says here as an assessment, and what I, as an individual see, looking at the scientific record, I still have a tricky decision. If I make my own personal assessment, which is similar to the one the political system has to make, my assessment would be that if we were a wise society, we would take steps now to reduce the long-term impact. Because it is not so much the impact on our own society, and our own agriculture, over which we have some control. It is the impact on the natural ecosystems.

If I might make just one quick other remark. James Lovelock is the man who introduced the Gaia hypothesis some years ago. He drew a loose analogy between the attitude of the Victorians when they discovered the beginnings of germ theory.

They looked at their cities. And they realized that some of the health problems they were faced with in their urban areas were due to just bad urban sanitation. They did not wait a century or so, first, to work out all the details of the biochemistry of all the diseases, which we are still in the progress of doing.

They had a certain humility, and went about cleaning up the cities. I believe he was talking about London. And in the process, they wiped out all sorts of health problems, many of which they did



not know anything about. We probably are faced with a similar situation with the global climate system. We need to clean up our emissions. It is not just the things that we understand, or we think we understand.

It is all the surprises that lie along the way, particularly in terms of interaction with the biosphere, coupled with the impact that we are having on the forest ecosystems, just because of our civilization.

My general conclusion is, again, that if we were wise, we would slow down and do what we can to minimize the impact. It buys us some more time. It buys us time for our observational and theoretical studies. And in the process, we will minimize the climatic impact—whatever it is.

Senator GORE. I would like to shift gears, in the short time we have remaining.

Thank you, Dr. Betts.

We have Dr. Hall, Dr. Tilford, and Colonel Townsend here. They have listened to this very carefully. They have followed this discussion. They are, themselves, quite informed of these topics.

But they are also managing data bases and programs that produce raw data that can be enormously valuable in resolving the uncertainties, some of which we have discussed here today.

Do any of you have suggestions on how the Mission to Planet Earth, EOS, the Air Force's data bases can be modified, changed, improved, supplemented, in ways that will help us resolve these uncertainties better than we are currently planning to do?

Yes, Dr. Charlson.

Dr. CHARLSON. One of the things that is now evident is that we cannot consider the problem of the physical climate of the Earth by considering physics alone. We have to consider atmospheric chemistry—aerosol microphysics and all that is attendant upon that. And Alan Betts has just mentioned correctly that we have to understand the response of the biosphere and feedback that it might produce.

We must have, in the future, a much more interdisciplinary approach, an integrated approach, to the research, than we have had in the past. I think reductionist science has been very helpful in producing extreme excellence in narrow, tightly focused topics. But it has not done us well in terms of integrating complex subjects like this one.

So, my feeling, as a professor of interdisciplinary topics, and from that experience, is to suggest that in the future we need to stress——

Senator GORE. Interdisciplinary connections?

Dr. CHARLSON. Yes, not just with words, but actual deeds.

Senator GORE. Now, do you have suggestions for them on how to go about that?

Dr. CHARLSON. One of the ideas that has come to mind among a group of us that have been discussing this matter—the one that I reported on here—is that we need to have integrated research programs involving several agencies simultaneously.

For example, missing here today is the Atmospheric Chemistry Program from the Department of Energy, which has an explicit program studying the evolution of aerosol particles and their effect

on climate. That capability, along with the excellent capability for meteorology, and so on, in NOAA, the satellite capabilities in NASA, and the other broad scope of fundamental topics provided by NSF, will all be needed in a concerted fashion.

I see this as a very positive opportunity for the future, for integrating the research efforts—not to denigrate at all the focused reductionist science approaches, which we still need. But this is a new type of integration that previously we have not undertaken in a concerted fashion.

Senator GORE. Well, philosophically, that is a question that addresses civilization as a whole. But that is another topic.

Yes, Dr. Ramanathan.

Dr. RAMANATHAN. I think based upon the discussions that we have had today, you have probably picked up the message that we are arguing without having any data. And one of the major missing pieces of information is the water vapor distribution in the atmosphere.

One thing Professor Lindzen has accomplished is to highlight that. We should thank him for that. So, I think that is one thing I would like to see taken on an urgent basis, to see what we can do. Is there improved instrumentation available and aircraft, which are coming into play?

The second issue—I think I conveyed this before, but it will not hurt to state it again—is to support Dr. Hansen's small satellite mission. I think people are seeing their way about the need for such emission. But I would like to see that program accelerated.

For example, regarding the Earth radiation budget experiment, we do not have any more radiation budget data. And I am fervently hoping that the Earth Observing System Program would be accelerated. But if that cannot be done, I would like to see a small satellite mission accelerated—something in the next 2 or 3 years, if possible.

Senator GORE. I know that debate has raged in the program. If, at any point here, as the panel members are talking this "wish list" through, if you want to jump in, please feel free to do so.

Dr. Tilford.

Dr. TILFORD. I always have to jump in a little bit. I wrote a few notes to Mike during the discussion. I think much of today's discussion would not have been necessary, if we had had some water vapor measurements of significantly precise nature that we could answer this question. Ours do not exist today. We do not even have a demonstrated measurement in many cases. We do have, and will have—in the next year—a series of aircraft experiments to do some of these things. But that will not provide the global perspective. That requires, I believe, global moisture measurements—water vapor measurements—of the degree that we have on the drawing table, but which have not been implemented.

I think what you have heard here today, is a very loud requirement for getting long-term, calibrated, global data sets, so that many of these questions can be answered—not now, but 5 to 10 years from now.

Because if we do not have the data sets, 10 years from now we are still going to be having these hypothetical discussions about hypotheses, without having the information to validate them.



Senator GORE. Yes, Dr. Arking.

Dr. ARKING. I just wanted to point to that, in addition to water vapor, we have heard a lot of discussion about clouds. And we need to get good cloud data. I just want to allude to something in the statement that I submitted—that up to now, satellite cloud data sets have been based on sensors of opportunity—that is, sensors that were designed primarily for other purposes. And that a lot of my own work, and that of others, is being focused on developing techniques for improving the retrieval of cloud parameters from space, including the design of sensors that would be dedicated to the measurement of cloud parameters.

So, at some time, when it becomes feasible, I believe there will be deployment of dedicated sensors in space—coupled with field experiments that are now going on, to provide ground-based measurements, in situ measurements, of clouds, because not all of the parameters that are required can be obtained from space.

With a program that goes in that direction, we should be able to get the information that is needed to improve our models. And in that sense, I agree with—I think—most of our colleagues, that we are rather unsure about the magnitude, and even the sign of the cloud feedback.

So, in addition to water vapor, we are going to have to put in a concentrated effort on getting the information we need about clouds, so we can improve cloud parameterization in our models.

Senator GORE. Very good.

Now what about this where the Air Force is concerned. You talked about aircraft, Dr. Ramanathan. And you mentioned, Dr. Tilford, the LIDAR experiment. Is there a way in which an instrument package might be designed, which would be compatible with routine missions through the troposphere in various parts of the Earth that would be particularly helpful in this respect, yes?

Dr. RAMANATHAN. I think there is a particularly unique opportunity in terms of this remotely piloted aircraft that is being developed by the military. And I heard that there are only six of them are available. And that has the capability to almost monitor the planet from remote locations.

So, that is one area that is worth exploring.

Senator GORE. Yes, unfortunately—not out of this committee, but elsewhere—the RPV's were deemphasized. And that is one instance where the ball is squarely in our court. And it is not the only place, nor the only time, when the ball is in our court. But I think that needs to be addressed.

Dr. TILFORD. There is also a unit in the Department of Energy that is looking at the RPV, especially in connection with the ARM Program—Atmosphere Radiation Measurements—which is closely tied to something you heard about today. And I think it is extremely important to take advantage of the ARM Program for resolving some issues you heard about.

Senator GORE. Now I take it that there is agreement here that the role of clouds in climate change is correctly identified as the number one priority of the U.S. Global Change Program?

[No response.]

Senator GORE. I mean, I think the way you stated it officially was that you were looking at greenhouse gas-induced warming and so on. But the research priorities after that——

Dr. TILFORD. I think it is fair to say that it is the top research priority. But this is not to the exclusion of any others.

Senator GORE. Now, is there general agreement that water vapor in the atmosphere—and clouds, in particular—represent the most important factor in determining the amount of greenhouse warming we will experience, as $CO_2$ and other greenhouse gases increase?

Dr. RAMANATHAN. I would think the oceans need to be mentioned here. If you are looking at the total magnitude of equilibrium warming, your statement is true. But if you are interested in what is going to happen in the next 20 years, the ocean, and its coupling with the atmosphere, equally could play the same role.

Senator GORE. In determining the amount of greenhouse warming?

Dr. RAMANATHAN. Yes.

Dr. TILFORD. I think that that is certainly true. But the cause of this unknown sink of $CO_2$, whether it is in the ocean, or whether it is in the biosphere, I think this is just another example of coupled greenhouse gases that are so important to look at from an integrated point of view.

So, I think this ranks right up there, in terms of——

Senator GORE. That is likely to be our next roundtable discussion, to look very closely at that collection of uncertainties.

Now, as has been made clear, the way clouds are represented in global circulation models, will have an important influence on the amount of global warming that those models predict.

Is there general agreement that the models can, and must do a better job of modeling clouds?

Dr. ARKING. Sure.

Dr. TILFORD. That is, if resources are available to develop those models.

Senator GORE. Now, is that an acknowledgement that the ball is in your court, or a firm placement of it in our court?

Dr. TILFORD. In our, in our court.

Senator GORE. OK.

Dr. LINDZEN. Senator, may I have one gloss on that?

Senator GORE. Yes, please.

Dr. LINDZEN. Which is, that in modeling clouds better, or modeling water vapor better, or any of this modeling, by means of the large-scale, general circulation models, is not an economical tool. The cloud physicists, the people looking at the cloud microphysics need to find out what it is you put in the large-scale models. And they should not—I think—be ignored in that.

Dr. TILFORD. I think the whole revolutionary approach to modeling—I think we almost have to look at the global change models of GCM's. But at the same time, I think we have to do it in a modular context, where not only do we just put in cloud microphysics, but we put in vegetation, biology, and feedbacks.

Dr. LINDZEN. But also put in something that means something. Because it is the easiest thing in the world to put a process in the model.



Dr. TILFORD. We need to use physics first, right?

Senator GORE. All right, now which ongoing, or planned, federally funded research programs do you, on this panel, believe will do the most to elucidate the role of clouds in global warming? And I would like to see if the group can agree on three or four.

Dr. Ramanathan.

Dr. RAMANATHAN. I would say that the first is the Atmospheric Radiation Program, the DOE's own program. The second is an ongoing program, which is the International Satellite and Cloud Climatology Project. We are learning a lot more about the structure. And I think what I see missing here is, in terms of field observations, to see what really is happening in the atmosphere. And that is what I would like to emphasize, that remotely piloted vehicles, I think, will play a key role.

And I have a suggestion—since Dr. Mike Hall is here—that in my own work, the Nature paperwork—the major message was that there is a spectacular, natural experiment on this coupling of ocean-warming, atmospheric convection, and clouds. That is the El Nino simulation. I would really like to see—this program is ending—it is called the TOGA program. And I would like to really see that continue, and support given for that to be continued, but then broaden the scope.

There, I believe—it is that testing ground, we can test all of these ideas. That is now being planned now, continuing the program.

Senator GORE. Before I ask Dr. Hall to respond, do we have a second to the motion? Does anybody else agree that this would be a good initiative?

Dr. ARKING. Yes, second.

Dr. TRENBERTH. Perhaps I can comment—I am on the International Scientific Steering Group for TOGA. We just had a meeting a short time ago, and there was very strong support for continuing the TOGA program internationally.

One of the main reasons why it may not be continued is because of the perception that in the United States it is not a feasible thing to do, when you say you are going to finish a program on a particular date. So, there is likely a sort of a relabeling of TOGA Program—Tropical Ocean Global Atmosphere—but certainly on the activity related to TOGA, there is a very strong worldwide consensus that it should continue.

Senator GORE. Dr. Lindzen, do you agree with that?

Dr. LINDZEN. Yes, I do. I believe—I think El Nino gives one a chance. And we now know that Spencer and Christie—to see a situation when the tropics have their mean temperature change. And if one can examine the water vapor of the whole tropics, on El Nino, and La Nina, one has pretty much what one wants—albeit maybe at a magnitude that is marginal.

Senator GORE. I thought I remembered you actually suggested that in your original paper on this subject.

Dr. LINDZEN. Yes.

Dr. TILFORD. Could I comment first, and save maybe a little embarrassment here?

I do believe one of the casualties in this year's budget process was, in a sense, the lack of ability of NOAA to continue this pro-

gram at the requested level. I think, as you have heard around the table—and I think it is much more pervasive than that—but there is a serious concern about the ability to continue this program at the requested level, based on the fiscal year 1992 budget approvals.

Senator GORE. Let me explain what many of the panelists probably already know very well—and that is that it is not uncommon for agency heads to have a clear understanding of what the research needs are and to make requests. Accordingly, even after all the unnecessary fluff and fat is cut out, a lot of times—especially lately—some very deep cuts are made, which many agency heads disagree with. And then when they come up to testify, they are constrained to be loyal to the President's authority to establish the administration's overall priority, even if they do not really agree with it.

And I am going to assume from Dr. Tilford's chivalrous act, that that is probably the case where Dr. Hall is concerned? You may or may not comment, as you wish, Dr. Hall.

Dr. HALL. I would like to comment, Senator.

Shelby Tilford did, indeed, do me a favor. Because I would like to set budget considerations aside.

Senator GORE. Before you do, I would like to say in defense of the White House, Congress made this particular cut. The request from the administration as a whole was $78 million. And Congress cut it to $47 million. Is that correct? And I very much disagree with that, and will report to my colleagues that one of the micro issues upon which there was near unanimity upon this panel—if not unanimity—is that we really need to rephrase that.

But go ahead.

Dr. HALL. I might say, in regard to this issue that you mentioned, that it impales to each of the members of this panel to discover in details, the things we are thinking about suspending indefinitely as a result of that appropriation. So, they do have their impact.

But I would like to make a more positive statement. Budget issues aside, I would like to go on record agreeing with he proposition which Ram has put forward.

I think that TOGA might properly have at least two children. One of them is a system of observations and continuing modeling through which actual predictions of some important aspects of interannual change are done, and are used by societies around the world.

But second, TOGA might have as a legacy, a unique set of programmatic machinery, and a certain momentum in a very important natural laboratory on this Earth—a part of the system we are beginning to understand. A part of the system where an integrated approach, as I said earlier, to clouds, energy, water, aerosols, radiation, might be possible. And I have been encouraging the academy to think about the events after TOGA in both of those modes, so that we might take advantage of this terribly important research opportunity, while at the same time taking TOGA, proper, to its logical conclusion, which is inter-annual predictions.

I would like to make one other point, while I have the microphone, if I may—Dr. Charlson referred to a world in which a meteorologist cannot be expected to go do the plankton and air sea exchange process studies that is necessary to look at dimethylsulfide, and so on; a world that is fragmented by disciplines.



We do not have, in the Untied States, or in the world, a single strategy for studying this problem. There is not a coherent package of thought around which we can design any experiment. And when we—we must move toward that. We must move toward looking at all aspects of a problem at the same time, so that we have closure; so that we can arrive at a logical conclusion. I think it will take us years to formulate that strategy—at least 2 or 3 years—but I think we must work much harder to formulate that integrated strategy that builds around a single notion of how the system operates. So that when we fail, when we are wrong, we will know, and can take the next steps.

Senator GORE. May I say, before concluding, we could continue this discussion for a long time, and still not exhaust the very interesting differences of opinion, and questions that need to be explored. But unfortunately time is a factor for us, and we have exceeded our time.

I hope this series of earth science roundtables will continue, as successfully as I think this one has been, in improving the understanding of this committee of what the state of the debate in the scientific community is, and in producing some concrete suggestions for how we can better discharge our responsibilities in assigning priorities to research dollars.

I might say that if this series does continue, according to plan, the plan includes an annual update on the discussions in each area, not as lengthy as the initial discussion in each area. But I would hope that some, or all, and perhaps others, might assemble here in the next year, to review the discussion after some further evidence is acquired; after we have had a chance to respond in the Federal programs here; and, for example, respond to Dr. Charlson's suggestion that we search for ways to bring things together a little bit more.

And Dr. Ramanathan, I hope you and others will not skim over the idea that RPV's aside, piloted aircraft might also play some role. And if, after giving some thought to that, some imaginative way might be found, I would like to suggest that if the scientists in this area, and any of you who wish to be included in that want to pursue that idea, I will be glad to set up a meeting and discussion with the folks in the Air Force who are quite responsive on this subject.

Dr. RAMANATHAN. Certainly.

Dr. LINDZEN. What you are suggesting is the Air Force might do what Boeing 747's do on an opportunity basis, take data?

Senator GORE. Yes, yes.

Dr. RAMANATHAN. Mr. Chairman, I am certainly interested in exploring that.

Senator GORE. Now, last, I think we can all agree that we have a very important problem to address here, that many of you have devoted many years of your lives to it. I want to thank all of you for sharing in this discussion today. I just hope that in the next few years, there can be as much progress in the political arena, as there has been in the scientific arena. We cannot wait until we have all the answers. I want to identify with the eloquent state-

ment of Dr. Betts on that particular point—and others, I might say. You just do not wait until you know when your house will burn down in order to buy fire insurance. And I do not think we can afford to wait until all of the uncertainties have been removed before we decide it is time to take steps to stop this dramatic and unprecedented increase in the greenhouse gases.

But improving our knowledge base is the place to start. And I appreciate all of you helping in that task today.

Thank you very much.

[Whereupon, at 1:13 p.m., the committee adjourned.]

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