Anthropogenic Climate Change: Areas of Uncertainty

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September 17, 1996

Testimony at the United States Senate hearing on

"U.S. Climate Change Policy"

Held by the Energy and Natural Resources Committee
Chairman: Honorable Senator Frank H. Murkowski (Alaska)
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Honorable Chairman and Honorable Members of the Senate Energy and Natural Resources Committee:

I respectfully submit the testimony below, in response to your letter of September 9, 1996, in which you raise the following important and fundamental issue:

> "Whether or not there is sufficient scientific certainty about the question of anthropogenic climate change to justify urgent actions to limit greenhouse gas emissions, and where there are areas of uncertainty that merit further emphasis and scientific study."

My testimony takes into consideration the following statement (paraphrased from your letter) by the Under Secretary of State for global affairs, The Honorable Timothy E. Wirth:

> "Continued buildup of [greenhouse] gases will enhance the natural greenhouse effect and cause the global climate to change," and that "science calls upon us to take urgent action."

My Background: I published my first paper in this field on the greenhouse effect of CFCs in 1974, followed by papers on the climatic effects of carbon dioxide, water vapor and ozone during the succeeding 10 years. A variety of climate models were employed in these studies. For the past 12 years, my work has focused on the role of clouds in climate and climate change using satellite radiation budget measurements, aircraft, ship and surface measurements.

Caveat: In spite of working nearly 25 years on some very formidable and challenging problems, I have never faced an issue as difficult as the one raised in this testimony. As a scientist with very little training or preparation in such policy related issues of great economic consequences, I must restrict my statements below to the scientific issues. This is only natural, for the policy issues rarely arise during the conduct of science. However, conscientious attempts will be made to state the problem in a format that is not only scientifically rigorous, but also informative enough for a non-specialist to address the policy issue at hand. As another cautionary statement, I must add that the science of climate change has witnessed: on the one hand, many surprising discoveries that tend to decrease the uncertainties; and on the other hand, the development of unanticipated major gaps in our knowledge that lead to more skepticism. The statement below should be viewed as a personal (as opposed to a consensus view) snap-shot of the problem as it is understood today.

The text begins with the facts, moves on to deductions based on sound physical principles, and concludes with model predictions, recent findings and the emerging uncertainties. The essence of the testimony is summarized first:

- For scientific, as well as policy purposes, it is convenient to separate the problem into two sub-components: the greenhouse effect; and the global warming that results from the greenhouse effect.
- The natural greenhouse effect is provided by water vapor, carbon dioxide, clouds and other trace gases and is an observed and observable fact.
- A build up of the greenhouse gases would enhance the greenhouse effect.
- Fundamental physical principles such as global energy balance and Planck radiation law lead to the deduction that, an enhancement of the greenhouse effect would lead to a global warming, if it is not offset by competing natural variations or other compensating changes by human activities.
- The magnitude and timing of the warming are highly uncertain (about a four fold range in the predicted magnitude), for these estimates are based on climate models which require further refinement in the treatment of clouds, aerosols and ocean-atmosphere interactions.
- The uncertainty is compounded by the recent findings that anthropogenic activities may be modifying several other climate forcing factors. Of these, the cooling effect due to tropospheric aerosols and the warming effect of tropospheric ozone require focused studies, because: (1) the magnitude of their effects are estimated to be large in the northern hemisphere continental regions; and (2) their radiative cooling effects are largely based on aerosol-model studies which require experimental verification.
- Another area which requires further scientific study is the magnitude of atmospheric absorption of solar radiation in clear and cloudy regions. Six independent studies (documented in the text) conducted in the US, Germany and Switzerland have identified a large and systematic discrepancy between climate models and observations. The model atmosphere absorbs less solar radiation than indicated by observations. The cause of this excess absorption, its magnitude, as well as whether it is in clear or cloudy regions, are being debated actively in the open literature.

The sources of uncertainty identified above are in addition to those identified in earlier reports (e.g., IPCC reports) which include: cloud, water vapor and ocean feedback effects on climate change. Likewise, areas that require focused efforts (in addition to the aerosol and the solar absorption issues) include: development of coupled land-ocean-atmosphere models; development of long term surface, in-situ and space borne observing systems; and documentation of present and past climate changes. With respect to the policy related question, I offer the following opinions.

- We absolutely have to accelerate the pace of research, if we are going to come to grips with the scientific uncertainties soon enough to have answers that policymakers need. Science can help provide a basis for sound policy, but only if we do the research in a timely and thorough way.
- I conclude with a view I share with many of my colleagues (e.g., see R. Somerville: The Forgiving Air: Understanding Environmental Change, Univ. of California Press, 1996): Some "actions," like promoting energy efficiency and energy conservation may be an attractive policy alternative, in view of such large uncertainties in the predicted anthropogenic climate changes.

Changing Chemical Composition of the Air: A Factt

Observations over the last two decades have documented, beyond a reasonable doubt, that the concentrations of several gases in the atmosphere are increasing substantially due to human activities. In addition, a compelling case can be made that the increase began more than a century ago. The pollutants that concern us the most are: carbon dioxide (CO_2), methane, halocarbons (e.g., CFCs), and nitrous oxide. Collectively, these gases are known as the greenhouse gases, which surround the planet like a blanket.

The Natural Greenhouse Effect: A Factt

Heat Balance: A major fraction of the incoming solar radiation is absorbed by the atmosphere and the surface, which heats the earth-atmosphere system. In turn, the surface and the atmosphere radiates this heat to space as heat (alternately known as infrared or simply IR) radiation. Thus the planet, as a whole, heats by absorbing solar radiation and cools by giving off IR radiation to space.

The Natural Greenhouse Effect: The important naturally occurring atmospheric constituents that contribute to the greenhouse effect are: water vapor, carbon dioxide and clouds, with smaller contributions from ozone, methane and nitrous oxide. These gases and clouds reduce the IR radiation emitted by the surface which would, otherwise, have escaped to space. *The reduction in the planetary IR cooling (to space) is the so-called greenhouse effect.*

This reduction results from the fact that the atmospheric greenhouse gases and clouds absorb IR radiation emitted by the warmer surface, and emit it to space at the much colder atmospheric temperatures. The net effect is that, the gases absorb more IR radiation (from the surface) than they emit to space. In other words, the gaseous blanket traps the heat energy of the planet.

Evidence for the Greenhouse Effect: Radiation budget satellites routinely measure the outgoing IR radiation emitted by the planet to space. These data reveal that, globally, only about 60% of the IR energy emitted by the surface escapes to space. The remaining 40% is effectively absorbed by the atmospheric gases and clouds, thus reducing the IR cooling to space by about 40%; in energy units, the global natural greenhouse effect of the atmosphere is about 150 W m^{-2} [Watts per square meter of the earth's surface; 1 Watt is 1 Joule of energy flow per second], with an uncertainty of about 10 W m^{-2}. This number (150 W m^{-2}) should be compared with the global absorbed solar radiation by the planet, which is about 235 W m^{-2}. Clearly, the natural greenhouse effect is almost as important as the solar radiation in maintaining the climate.

NASA Earth Radiation Budget Satellite data (Barkstrom, *Bull. Am. Met. Soc.*, 1989) were used to derive the greenhouse effect of atmospheric gases over the ocean (Raval and Ramanathan, *Nature*, 1989). The data were shown to be in close agreement with that predicted by models.

Anthropogenic Enhancement of the Greenhouse Effect: A logical extension of observations

It naturally follows from the above data that the observed increase in greenhouse gases will further reduce the IR cooling to space, i.e., enhance the greenhouse effect. This reduction in IR cooling to space is usually referred to as the direct radiative forcing (e.g., see IPCC, 1990). During the last fifteen years, there have been numerous national and international attempts to estimate this enhancement of the greenhouse effect, culminating in the IPCC studies. Earlier studies initiated by the WMO (Ramanathan, Cicerone, Singh, and Kiehl, *J. Geophys. Res.*, 1995; Ramanathan and 10 Co-authors, *Rev. of Geophys.*, 1987) concluded that human activities have enhanced the greenhouse effect by about 1.8 W m^{-2} from the pre-industrial era to the year 1980, and that it is increasing by about 0.4 W m^{-2} for the decade of the 1980s. This is consistent with the most recent IPCC assessment (IPCC 1995): the direct radiative forcing of the long lived trace gases from the pre-industrial era to the year 1992 is 2.45 W m^{-2}. Thus there is no major discrepancy between the various studies in the estimated anthropogenic enhancement of the greenhouse effect. However, new findings unanticipated by the earlier studies, make the total radiative forcing significantly different from the direct greenhouse forcing, and these will be highlighted later.

In summary, observations and model studies demonstrate that the build up of the greenhouse gases should have enhanced the greenhouse effect by about 2.45 W m^{-2} between the pre-industrial era to the present.

Global Warming Deduction based on sound physical principles:

How would the planet respond to this additional heating? It will warm up and radiate more energy until the balance between incoming solar and outgoing solar radiation is restored. This is because, the Planck radiation law, one of the fundamental laws of physics, dictates that the IR radiation increases with the temperature of the radiating substance.

Hence based on satellite radiation budget observations, sound physical principles and laws of physics, we can state with confidence that the increase in greenhouse gases, if not offset by other compensating anthropogenic changes, should cause global warming. There is near unanimous consensus in this statement.

In summary, the global warming is a consequence of the global energy balance principle and the Planck radiation law.

Magnitude of the Warming: Model predictions

The information given up to this point is largely of academic interest. We really want to know:

- How large is the warming going to be?
- How soon will it manifest?
- What are the regional consequences, particularly with respect to extreme weather events?

It is in answering these questions that we slip from facts and sound physical principles to model predictions that are yet to be verified unambiguously. Climate modeling groups the world over, and the US in particular, have made impressive progress in refining their models by including processes that are important for climate. Such models (one, two and three dimensional models) are converging on global surface temperature changes that are within a factor of four from each other. Let us first examine the model prediction for the global warming: The direct radiative forcing of the greenhouse gases has committed the planet to about 0.5 to 2 C global warming, alternately referred to as the equilibrium warming; about a third to two-third of this should have happened by now; the remaining is stored in the oceans -- it may take several decades to longer than a century to realize the equilibrium warming. In other words, even if the atmospheric concentration of all gases were held fixed indefinitely into the future, at their 1992 values, the planet would warm by about 0.5 to 2K (from the pre-industrial era surface temperature).

The empirical climatologists also seem to be converging to the opinion that the planet has warmed, albeit erratically, during this century. There seems to be a rough agreement between the models and the empirical data in the magnitude of the surface warming, but even for this rough agreement, the models require consideration of additional factors such as solar forcing, aerosols, stratospheric ozone depletion, amongst other factors.

The evidence we have is still ambiguous and fundamental scientific uncertainties remain, which will be taken up next.

Uncertainties and Areas of New Research:

The various sources of uncertainties and areas that require focused study have been listed in the summary section at the beginning of the testimony. Here, I focus on 2 important issues that fall within my area of expertise.

I. Other Climate Forcing Factors

Until about five years ago, it was generally thought that the direct radiative forcing due to the build up of the greenhouse gases was the dominant human effect on climate. This picture has changed considerably, as can be seen by comparing the papers published in the mid 1980s with the more recent ones. A flavor of this change can be gleaned by comparing IPCC 1990 with IPCC 1995.

Modeling attempts, to reproduce the details of the observed surface temperature changes of the last century, have shown that decadal changes in several poorly observed climate forcing factors may play an important role in governing the decadal changes in model temperatures (e.g., see IPCC, 1995). These factors include: cooling effect due to the increase in tropospheric aerosols (sub-micron size particles); cyclical variations in the incoming solar radiation; warming effect due to an increase in the tropospheric ozone concentrations; cooling due to the decrease in the stratospheric ozone concentrations; just to name the most important ones. Globally, the direct forcing due to the greenhouse effect still dominates the signal (in the models), but regionally, these other factors can compensate it completely or amplify it significantly. The most important of these is the tropospheric aerosols, which may introduce a large uncertainty in the climate change predictions for the northern hemisphere extra-tropical regions.

Tropospheric Aerosols: Biomass burning and anthropogenic sulfur dioxide give rise to aerosol particles in the lower atmosphere, which scatter the solar radiation back to space and exert a cooling effect. The life times of these particles are sufficiently small (days to weeks) that their effect is concentrated in regions were the pollutants are released. Over the north eastern United States, Europe, Asia and other industrialized regions, the aerosol effect is particularly large. The resulting radiative forcing pattern is complex, with strong regional and seasonal variations. The aerosols are also predicted to modify cloud properties, which in turn can alter the radiative forcing. The net effect of the aerosols would depend on how the atmospheric circulation redistributes the aerosol radiative forcing. Our understanding of the aerosol forcing is largely based on models and needs to be confirmed by direct observations of: how human activities are modifying the aerosol concentrations; and, how the anthropogenic aerosols are modifying the radiative forcing.

II. Atmospheric Solar Absorption

One of the fundamental quantities that determine the climate including the atmospheric and oceanic circulation is the magnitude of the solar radiation absorbed at the surface and within the atmosphere. Recent attempts (Ohmura and Gilgen, *Ann. Geophys. Union Geophys. Monogr*, 1993; Wild et al, *J. Climate*, 1995; Cess et al, *Science*, 1995; Ramanathan et al, *Science*, 1995; Pilewskie and Valero, *Science*, 1995; and, Arking, *Science*, 1996) at comparing model simulations with available surface observations have concluded that there is a systematic discrepancy between models and observations in the estimated solar absorption. Globally, the surface solar absorption simulated by the models is systematically larger by about 15 to 30 W m^{-2}. The general consensus among the above studies is that the models allow too much solar radiation to be transmitted through the atmosphere, i.e., the model atmosphere absorbs about 15 to 30 W m^{-2} less solar radiation than indicated by observations.

There is, however, considerable debate and controversy over: whether this excess absorption is as large as suggested by the above studies (e.g., Li et al, *Nature*, 1995; Stephens, *Science*, 1995); or it is in the clear skies (Arking, 1996) or in the cloudy skies (Cess et al, 1995; Ramanathan et al, 1995; and, Pilewskie and Valero, 1995) or in both regions (Wild et al, 1995). The physics behind this excess absorption is also unclear. However, because of the large magnitude of this missing source of atmospheric absorption, it can have a significant impact on model simulations of the present climate (Kiehl et al, *J. Climate*, 1995). The impact, this excess absorption would have on climate change predictions is unknown at the present.

In view of the importance of the problem to climate models, the Department of Energy has assembled a team of scientists (from many sides of the excess absorption issue) who are conducting field experiments at the DOE-ARM site in Oklahoma to understand the magnitude and nature (in clear or cloudy skies) of the discrepancy between models and observations. If the Oklahoma studies confirm the large magnitude of the excess absorption, extensive field observations in various climatological regimes of the globe would be required to unravel the causes of the unexplained solar absorption.