SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

Witness List*

Hearing on

Global Change Research: Ozone Depletion and Its Impacts

Friday, November 15, 1991, 9:30 a.m.

in room SR-253 of the Russell Senate Office Building

1. Sen. Gore

Roundtable Discussion Participants:

No Statement — Dr. Daniel L. Albritton, Director, Aeronomy Lab, National Oceanic and Atmospheric Administration, Boulder, CO 80303

2 Dr. Stephen Anderson, Director, Technology Transfer and Industry Program, U.S. Environmental Protection Agency, Washington, DC 20460

3 Dr. Margaret L. Kripke, Chairperson, Department of Immunology, M. D. Anderson Cancer Center, University of Texas, Houston, TX 77030

4 Dr. Ari Patrinos, Acting Director, Environmental Sciences Division, ER-74, U.S. Department of Energy, Washington, DC 20585

5 Dr. Alan H. Teramura, Professor and Chair, Department of Botany, University of Maryland, College Park, MD 20742

No Statement — Dr. Shelby Tilford, Director of Earth Science and Application Division, National Aeronautics and Space Administration, Washington, DC 20546

6 Dr. Jan C. van der Leun, Institute of Dermatology, University Hospital Utrecht, Heidelberglaan 100, NL-3584 CX Utrecht, The Netherlands

6 a Executive Summary, Scientific Assessment of Stratospheric Ozone 1991

7 Dr. Robert T. Watson, Branch Chief, Upper Atmosphere Research Tropospheric Chemistry, Earth Science and Space Applications Division, National Aeronautics and Space Administration Headquarters, Washington, DC 20546

8 Dr. Susan Weiler, Executive Director of the American Society of Limnology and Oceanography, Department of Biology, Whitman College, Walla Walla, WA 99362

9 Dr. Robert Worrest, Program Manager, Stratospheric Ozone Research Program, U.S. Environmental Protection Agency, Washington, DC 20460

*Not Necessarily in Order of Appearance

STATEMENT OF SENATOR ALBERT GORE, JR.

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

HEARING ON OZONE DEPLETION AND ITS IMPACTS

FRIDAY, NOVEMBER 15, 1991

Good morning. Today, the Commerce Committee will examine the latest information on the damage we are doing to the earth's protective ozone layer and what it means to us, our health, our food supply, and our global environment.

On October 22, the United Nations Environmental Programme released the executive summary of a report entitled, "A Scientific Assessment of Stratospheric Ozone, 1991." This is one of three parts of a UNEP assessment of ozone depletion which is due to be released in its entirety early next year. This is the second such assessment done since the Montreal Protocol on Substances that Deplete the Ozone Layer was signed in 1987. The Montreal Protocol called for these international assessments so that policymakers would have the information they need to revise and update the Protocol as new scientific data came available. Like the first assessment released in 1989, this new report includes disturbing new data indicating that ozone depletion is even more serious than we thought.

Many of our witnesses today were involved in writing the 1989 assessment, which concluded that ozone depletion was occurring much faster than most models predicted. As a

direct result of that report, the Montreal Protocol was amended to require a more rapid phase-out of CFCs, halons, and other ozone-depleting chemicals.

According to the report released this year on October 22, ozone depletion is occurring even faster than we thought in 1989. And it is occurring over more of the globe, throughout most of the year. New data provides clear evidence that ozone depletion is occurring not only in the winter, but in the spring and summer as well--when plants, animals, and people are most vulnerable. This ozone depletion is occurring not only in the Antarctic Ozone Hole, but also in the Arctic and at mid-latitudes, over our heads here in the United States. Worst of all, it appears that ozone depletion is accelerating.

According to the data, the ozone layer over the U.S. is thinning between 3 and 5 percent per decade. According to Sherwood Rowland, who testified before this Committee in April, the ozone layer has thinned about 10 percent since the 1960s. This is significant; it's widespread; and it will have major impacts on the environment and on people worldwide.

We are only now determining what those impacts will be. Unfortunately, there has been little research on the impacts of ozone depletion and increased ultraviolet radiation. Until recently, much of the data on the impacts of ultraviolet radiation has been preliminary and incomplete. Fortunately, there have been a number of good, solid studies completed in the last year or two that give us a clearer

picture. The new UN report effectively summarizes that new research. It is provides the most thorough assessment to date of the impacts of ozone depletion

And the news is not good. Researchers here today have discovered that increased ultraviolet radiation will reduce the quantity and quality of crops, increase skin cancer, suppress the human immune system, and disrupt marine ecosystems. According to the report, a 10 percent decrease in ozone will lead to between 1.6 and 1.75 million additional cases of cataracts per year world-wide and at least 250,000 additional cases of skin cancer per year. There are indications that increased ultraviolet radiation suppresses the human immune system that protects us from disease. It is now clear that ozone depletion will directly affect the health of millions and millions of people.

Ozone depletion will have major impacts on ecosystems as well. Trees, plants, plankton all seem vulnerable to ultraviolet radiation. And no doubt, there will be other serious consequences, many which we cannot yet anticipate, due in part to a lack of research.

Last year, the Federal government spent almost $1 billion on global change research, most of it at agencies under the jurisdiction of this Committee. I feel strongly that we need to devote more of that money to research on the impacts of ozone depletion. We must know more about the consequences of the damage we are doing to our global environment.

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 more work is needed.

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.

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November 14, 1991

Testimony of Stephen O. Andersen, Senate Committee on Commerce, Science, and Transportation: Hearing on Global Change Research: Ozone Depletion and Its Impacts, Friday, November 15, 1991

My name is Stephen O. Andersen. I am appearing as Co-Chairman of the United Nations Environment Programme (UNEP Technical and Economics Assessment. I am not representing the Environmental Protection Agency. I am Director of Technology Transfer and Industry Programs in the Global Change Division, Office of Atmospheric and Indoor Air Programs, Air and Radiation, of the U.S. Environmental Protection Agency.

The 1991 UNEP Technical and Economic Assessment was undertaken by over 240 experts from 38 countries.[1] Hundreds of additional experts served as advisors to the six committees and as peer reviewers. These include U.S. and foreign industry, government, and science experts.

The Assessment describes current uses and quantities of controlled substances, estimates the technically feasible phaseout dates, estimates the quantity and time period for use of transitional substitutes, and specifically describes the implications of a 1997 phaseout. The assessment will not be final until December but I am pleased to report on the consensus findings and conclusions as reported in the Executive Summary:

> Since 1986 there has been forty percent worldwide drop in the production of CFCs--this is faster than predicted by the 1989 Assessment and faster than the controls of the Montreal Protocol.
>
> Several multinational companies are eliminating the use of ozone-depleting substances far faster than even the most stringent regulation. By January 1992 the first companies will have eliminated the use of CFC-113 solvents in all their worldwide operations; halon and CFC recycling will be accepted worldwide; the first HFC-134a automobile air conditioners will be commercialized, and many other ozone-safe technologies will be available. The first HFC-134a domestic refrigerators will be commercialized in 1992.

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[1]Australia, Austria, Bahamas, Belgium, Brazil, Canada, Chile, China, Denmark, Ecuador, Egypt, France, Germany, India, Indonesia, Italy, Japan, Jordan, Kenya, Malaysia, Mexico, Netherlands, New Zealand, Nigeria, Norway, Papua New Guinea, Singapore, South Korea, Sweden, Switzerland, Trinidad and Tobago, Tunisia, Uganda, USSR, United Kingdom, United States, Venezuela, and Yugoslavia.

The international fire protection community has virtually eliminated halon emissions caused by discharge testing and training and service emissions have been drastically reduced. Educational programs are proving successful as users move to alternative fire protection measures, where feasible, and voluntarily limit halon use to essential applications.

It is technically feasible in developed countries to phase out production of CFCs and halons by 1997 or earlier, 1,1,1-trichloroethane as early as 1995, and carbon tetrachloride in the vast majority of applications by 1995.

These rapid phaseout schedules require that the results of the toxicity tests, environmental assessments, and risk analyses conclude that the alternatives HCFC-123, HCFC-124, HCFC-141b, and HFC-134a can be safely used for refrigeration, air conditioning, insulating foam, and for some aerosol, sterilization and minor solvent uses; that these HCFCs and HFC are environmentally acceptable; and that they are commercially available in adequate quantities. A rapid phaseout will also require increased near-term use of HCFC-22 and HCFC-142b. The halon phaseout is contingent on the use of recycled halons as the prime supply of those agents.

There is no perfect substitute. Each substitute has difficult trade-offs in ODP of transitional substances, Greenhouse Warming Potential (GWP), energy efficiency, and toxicity. Trade-offs can be minimized and mitigated by recycling and bank management, by limiting the use of transitional or high GWP options to only where necessary, and by limiting occupational exposures. For small uses, there are no substitutes yet, but the Technical and Economic Assessment is optimistic.

It is critical to successful phaseout for developing countries that technologies are available, that supporting technical assistance and training is provided, and that adequate financial assistance is forthcoming. Several developing countries are entering into innovative technology cooperation projects. For example, Mexico has announced a goal of phasing out controlled substances on the same schedule as developed countries. The Mexican government and industry are making partnerships with the U.S. Environmental Protection Agency (EPA), the Industry Cooperative for Ozone Layer Protection (ICOLP), and Northern Telecom to phase out solvents. Similar partnerships may speed elimination in other developing countries.

3

EFFECTS OF ULTRAVIOLET-B RADIATION ON IMMUNE RESPONSES OF MICE AND MEN

Margaret L. Kripke, Ph.D.

Vivian L. Smith Chair in Immunology
Professor and Chairman
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United States Senate
Committee on Commerce, Science, and Transportation

Hearing on

Global Change Research: Ozone Depletion and Its Impacts

Friday, November 15, 1991

INTRODUCTION

The immune system is the body's primary defense mechanism against infectious diseases. In addition to providing protection against bacterial, viral, fungal, and parasitic infections, the immune system also protects against the development of certain types of cancer, particularly those associated with cancer viruses and UV radiation (1). Any impairment of immune function can jeopardize health by increasing susceptibility to infectious diseases, increasing the severity of infections, or delaying recovery from infections. In addition, impaired immune function can increase the incidence of certain cancers, particularly cancers of the skin (2).

Research carried out with laboratory animals over the past 15 years has demonstrated that exposure of the skin to UV-B radiation can suppress certain types of immune responses (3). These include rejection of UV-induced skin cancers (4) and melanomas (5); contact allergy reactions to chemicals (3); delayed-type hypersensitivity (DTH) responses to microbial and other antigens (6); and phagocytosis and elimination of certain bacteria from lymphoid tissues (6).

IMMUNOSUPPRESSIVE EFFECTS OF UVB RADIATION IN ANIMALS

Effects related to skin cancer. The realization that UV-B radiation can affect the immune system came from studies on the effects of UV radiation in experimental animals. Many years ago, we discovered that exposing mice to UV rays caused a systemic change in their immune system that rendered them incapable of resisting the development and spread of UV-induced skin cancers (4). We now know that the systemic change brought about by UVB irradiation involves the production of suppressor lymphocytes. These white blood cells are part of the immune system and are responsible for regulating the magnitude and duration of an immune response. The suppressor lymphocytes present in mice exposed to repeated doses of UV-B radiation prevent the development of an immune response against UV-induced skin cancers. Thus, these suppressor lymphocytes impair the body's natural defense mechanisms against skin cancer development (7).

Effects on other immune reactions. In trying to determine how exposing the skin to UV radiation could alter a systemic immune response, it was discovered that UV-B radiation can suppress other types of immune reactions, in addition to tumor rejection (3). For

example, mice treated with very low (suberythemal) doses of UV-B radiation fail to make a contact allergy reaction to chemicals applied through the irradiated skin. Instead, suppressor lymphocytes are produced. The mechanism involves an alteration in the activity of an immune cell present in the skin, the epidermal Langerhans cell, which normally picks up foreign substances in the skin, carries them to the lymph node, and stimulates the lymphocytes to initiate an immune reaction. Exposure of Langerhans cells to UV radiation renders them unable to stimulate the appropriate type of lymphocytes and instead, suppressor lymphocytes are activated (8).

With higher doses of UV-B, UV-irradiated mice lose their ability to respond to chemicals applied through unexposed skin (3). They also have a decreased delayed hypersensitivity response to a variety of antigens, including those of bacteria, viruses, and fungi (6). The delayed hypersensitivity response is a lymphocyte-mediated immune reaction that contributes to the destruction and elimination of various microorganisms. Suppression of this response by UV irradiation is also mediated by suppressor lymphocytes. This systemic effect of UV irradiation has been demonstrated to occur in several species of animals, to be produced with relevant doses of natural sunlight, to be due mainly to wavelengths in the UV-B region of the spectrum, and to increase in proportion to increasing doses of UV radiation (3). The effect is thought to be due to the release of chemical mediators from skin cells (keratinocytes) damaged by UV rays.

Effects on infectious diseases. The finding that UV radiation can suppress certain lymphocyte-mediated immune reactions raised the possibility that immunity to infectious agents might also be impaired in UV-irradiated animals. Some disease-causing organisms, such as *Leishmania*, *Malaria*, and *Schistosoma*, and the leprosy bacillus, gain entry into the body through the skin. It was therefore possible that the entry of such organisms through UV-damaged skin might lead to activation of suppressor lymphocytes instead of a protective immune response. Other infectious agents, including viruses, bacteria, and fungi, produce diseases within the skin, and in addition, many organisms are normally controlled by the delayed hypersensitivity type of immune response. In these instances, the systemic immune suppression resulting from UV-B-irradiation could increase the severity of the disease process and prevent the development of immunity against reinfection.

To date, these possibilities have been tested in only a few animal models of infectious diseases (Reviewed in 6). The infectious agent that has been studied most extensively is herpes simplex virus (HSV). It is well known that UV radiation can trigger active herpes virus infections in humans and experimental animals that harbor latent virus. Mice exposed to low doses of UV radiation before inoculation of HSV showed an increase in the severity of skin lesions and systemic disease. In addition, low doses of UV radiation suppressed the induction of delayed hypersensitivity to viral antigens and resulted in the production of suppressor lymphocytes.

In several murine infectious disease models, mice were given low doses of UV radiation to impair the function of epidermal Langerhans cells and then infected with various microorganisms at the site of UV irradiation. Infection of mice with *Leishmania* decreased the resultant delayed hypersensitivity response to this parasite and diminished immunity to reinfection. However, these low doses of UV radiation had no effect on the rate of infection with either *Leishmania* or *Schistosoma* parasites, nor did they affect the development of the delayed hypersensitivity response to a fungus, *Candida albicans* , or a bacterium *Mycobacterium bovis* injected subcutaneously at the irradiated site. The ability of the mice to clear mycobacteria from the lymphoid tissues was reduced, however, resulting in a prolonged and more severe infection.

Mice given doses of UV radiation sufficient to cause systemic immune suppression are unable to make a delayed hypersensitivity response to candida or mycobacteria injected at a non-irradiated site. Furthermore, such mice are more susceptible to the lethal effects of an intravenous inoculation of candida, and their ability to control mycobacterial infection is greatly reduced, probably because the macrophages from such animals have reduced phagocytic activity. The progression of chronic infection of mice with *Mycobacterim lepraemurium* is also accelerated in UV-irradiated mice. There is evidence to suggest that some of these effects of UV irradiation also result from the action of chemical mediators released from UV-irradiated keratinocytes.

IMMUNOSUPPRESSIVE EFFECTS OF UV RADIATION IN HUMANS

There is increasing evidence that humans are also subject to the immunosuppressive effects of UV radiation (Reviewed in 9). For example, exposing human skin to UV-B radiation damages the Langerhans cells and changes the immunologic function of the skin in a manner similar to that described in mice. Also, several investigators have documented changes in the proportions of different types of white blood cells in people exposed to natural and artificial sources of UV radiation.

Of great interest in this regard are recent studies by Streilein and colleagues demonstrating that applying a contact allergy-producing chemical to skin given suberythemal doses of UV radiation fails to induce the expected immune response in about 40% of normal subjects; in patients who have had one or more skin cancers, the proportion of non-responsive individuals approaches 100% (10). This study demonstrates that humans are subject to at least one of the forms of immunosuppression identified in mice and suggests, in addition, that susceptibility to UV-induced immunosuppression constitutes a risk factor for the development of skin cancer. A second study (11) compared the same immunosuppressive effect of UV radiation in different ethnic groups having different amounts of skin pigmentation. There were no differences in the immunosuppressive effect of UV radiation in persons with white, brown, or black skin, indicating that pigmentation is not protective against this form of UV-induced immunosuppression. Thus, the population at risk of immunological damage from UV radiation is much larger than that at risk of developing skin cancer. At present, the significance of this immunological alteration for infectious diseases in humans is unknown.

CONCLUSIONS

The immunosuppressive effects of UV-B radiation in laboratory animals are well documented. There is also evidence that UV-induced immunosuppression can worsen some infectious disease processes in animal models. Recent studies have shown adverse effects of UV radiation on immune cells and on some immune functions in humans, and these effects probably contribute to the induction of skin cancers in susceptible individuals. However, it is not known whether the immunological effects of UV radiation can contribute to increases in

the incidence or severity of infectious diseases in humans. This is the most critical unanswered question in attempting to assess the impact of ozone depletion on human health. Infectious diseases constitute an enormous public health problem worldwide, and any factor that reduces immune defenses, thereby increasing the incidence or severity of infectious diseases, is likely to have a devastating impact on human health. Studies suggesting that skin pigmentation is not protective against UV-induced immunosuppression imply that this effect of UV irradiation is not limited to the Caucasian population at risk of developing skin cancer, but may extend to other ethnic groups, as well.

Another urgent problem comes from studies in laboratory animals suggesting that some commercial sunscreen preparations that protect against sunburn do not protect against the immunosuppressive effects of UV radiation. If this is true, then the concept that individuals can protect themselves from the hazardous effects of sunlight exposure by the use of currently available sunscreens must be reevaluated.

Much more information is also needed on the mechanisms of UV-induced immunosuppression if we wish to be able to predict the immunological consequences of increased exposure to UV-B radiation.

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4

Statement of Ari Patrinos

Director of

The Environmental Sciences Division

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Office of Energy Research

U.S. Department of Energy

before the

United States Senate

Committee on Commerce, Science, and Transportation

November 15, 1991

Mr. Chairman and Members of the Committee:

Stratospheric ozone depletion and its implications for climate change are of great concern to the Department of Energy (DOE) and I welcome the opportunity to respond to your invitation to present the Department's views on these subjects.

The connection between increasing concentrations of greenhouse gases in the atmosphere and climate change has been investigated by DOE since 1978 when the term "greenhouse effect" was known only to a few scientists and science managers. The DOE program, which is integrated into the U.S. Global Change Research Program coordinated by the Committee on Earth and Environmental Sciences, has investigated all facets of the issue, from the carbon cycle and climate diagnostics to the effects on human and natural resources. Since 1988, DOE has quadrupled its annual research investment in this program to $77 million. The focus of our research program is on improving the capability to predict global and regional climate change. The component of our program most directly related to stratospheric ozone depletion involves modeling stratospheric chemical processes and their impact on climate change. DOE also supports research on the nature of ultraviolet radiation-induced damage to DNA and the repair of that damage.

DOE is concerned with the mounting evidence of stratospheric ozone depletion caused by chlorofluorocarbons (CFCs). The Executive Summary of the United Nations Environment Programme (UNEP) Stratospheric Ozone Assessment released on October 22, 1991, indicates that the situation is worsening. Strong Antarctic ozone holes have continued to occur and, for the first time, we have evidence of stratospheric ozone depletion over mid latitudes and the poles not

just during the winter but also during other seasons. Despite some remaining scientific uncertainties regarding the mechanisms driving ozone depletion, it is clear that action to curb CFC production and use is both justified and prudent. This action is in fact an integral part of the Administration's policy.

DOE would like to focus on statements in the Executive Summary of the UNEP report that may be perceived to have climate change implications for stratospheric ozone depletion. The statements appear to be based on calculations using simplified radiative transfer models and are not necessarily supported by existing data. Although the report is careful in describing a possible climate impact in terms of radiative forcing, it is important to emphasize that any impact on climate change would be highly uncertain.

Describing "Recent Major Scientific Findings," the UNEP Executive Summary asserted that, for the decade 1980-1990, middle- and high-latitude ozone depletion in the lower stratosphere would have canceled the radiative forcing caused by increases in CFCs at these latitudes. We underscore some of the uncertainties voiced in the report. First, we believe this conclusion is based on the application of a one-dimensional radiative transfer model over various latitudes and seasons using the measured changes in CFCs and ozone concentrations. Second, we believe that the calculations assumed that the entire ozone depletion occurred evenly over the bottom seven kilometers of the stratosphere; in fact roughly 20 percent of the observed ozone change actually occurred in the upper stratosphere. Third, there is a much stronger seasonal

and latitudinal variation in ozone as compared to CFCs and, therefore, the net effect on climate cannot be estimated by only considering global average effects. Fourth, the magnitude and even the sign of the change in the radiative forcing due to decreased lower stratospheric ozone concentrations are very sensitive to the assumed temperature change in the lower stratosphere. A decrease in lower stratospheric ozone concentration will perturb the radiative forcing in the troposphere through a number of distinct mechanisms involving changes in solar and infrared radiation. The effects can be separated into direct effects due to ozone changes and indirect effects due the accompanying cooling of the lower stratosphere. These distinctions may not adequately be taken into account with simple one-dimensional radiative transfer calculations such as those used in the UNEP study. Furthermore, any resulting climate change impacts would require the application of more comprehensive climate change models.

Simple explanations of complex climate phenomena can sometimes be wrong. For example, despite the earlier conviction that clouds and polar ice caps would provide positive feedbacks to a warming climate, recent research has suggested that the feedbacks may in fact be negative. The results of comprehensive modeling studies of the ozone-CFC greenhouse effect interaction that are planned during the next few months by many scientists involved in this assessment will substantially increase our understanding of these phenomena.

The Executive Summary also reports a number of other results regarding the greenhouse effect. DOE agrees with the statements in the Executive Summary regarding uncertainties in Global Warming Potentials (GWPs) for short-lived

atmospheric constituents. However, we remain concerned about the representation of the carbon cycle used in computing the GWPs for all greenhouse gases. In particular, the current representation of the atmospheric decay of carbon used in the 1990 Intergovernmental Panel on Climate Change (IPCC) Assessment, when used with best available historical data of carbon emissions from fossil fuel burning and land-use change, overestimates current carbon dioxide concentrations. Thus, it suggests a relative importance of carbon dioxide that may be larger than its actual importance in the atmosphere.

For the reasons stated, DOE believes that caution should be exercised before policy conclusions are drawn. The appropriate forum for assessing the climate change implications of ozone depletion is the IPCC process. We believe the IPCC Working Group on science should immediately take up this report with an eye towards providing a more in-depth assessment of its implications for climate change.

That concludes my statement. I will be happy to answer your questions.

STATEMENT OF

ALAN H. TERAMURA

PROFESSOR AND CHAIRMAN, DEPARTMENT OF BOTANY

UNIVERSITY OF MARYLAND

BEFORE

SENATE COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION

FRIDAY, NOVEMBER 15, 1991

Mr. Chairman, members of the Committee, my name is Alan Teramura. I am a Professor and Chairman of the Department of Botany at the University of Maryland. My background is in physiological ecology and I have been conducting studies on the potential impacts of increases in solar ultraviolet (UV) radiation resulting from stratospheric ozone depletion on crops and forests for over the past fifteen years. I have worked closely with a number of U.S. organizations, including the National Academy of Science, the Environmental Protection Agency and the Department of Agriculture. Additionally, I have served as a panel member on the biological effects of ozone depletion for the United Nations Environment Programme and maintain close collaborations with scientists in the Federal Republic of Germany, Sweden, England, Japan, and India. I also helped develop a research program coordinated with the International Rice Research Institute in the Philippines to study the effects of increasing UV radiation on tropical rice, the world's most important crop plant. I am appearing before you today to outline the potential consequences of increases in solar UV radiation on crops, forests, and natural ecosystems.

Over the past 15 years, the scientific community has screened over 300 species and cultivars of crop plants and alarmingly, over one-half of these seemed to be

sensitive to UV radiation. Among the most sensitive plant groups include peas, beans, squash, melons, and cabbage. For budgetary and logistic reasons, most of this screening was performed indoors under controlled environment conditions. Without going into the specific reasons, we now know that plants are generally more sensitive to UV radiation under these controlled environments than outdoors. To date, only a dozen studies have been performed outdoors in the field on about 20 species of crop plants. Despite the many problems associated with these field studies, crop yield was reduced in nearly half of these studies. In a detailed field study conducted at the University of Maryland, several soybean cultivars were grown during a 6-yr period from 1981-1986. Increased UV was supplied by artificial sunlamps which simulated up to a 25% ozone depletion. In a particularly sensitive soybean cultivar, yield was reduced by 20-25% by a UV level simulating a 25% ozone depletion. In addition to quantitative reductions in yield, quality can also be adversely affected as seen as reduced protein and oil content in seed of UV irradiated plants. It is difficult, if not impossible to extrapolate these results to predict total soybean yields for the U.S. or the world under various ozone depletion scenarios, since several hundred soybean cultivars are currently grown worldwide and thousands of new experimental lines are being continually developed. To date, only about 50 cultivars have been examined for UV sensitivity and approximately half of these are sensitive based on controlled environment studies. But this suggests that the other half are somewhat resistant and therefore some degree of UV resistance already exists in our modern soybean germplasm which may allow breeders to develop more UV resistant plants in the future. What is presently unknown is whether these UV resistant cultivars might also carry some unwanted traits such as increased disease sensitivity, higher water or fertilizer requirement, etc. Preliminary data also show a similar degree of variation in UV sensitivity for rice, with both very sensitive and very resistant cultivars identified thus far. Therefore crop breeding may be one avenue available to us to help mitigate the damaging effects of UV radiation.

Although forests represent up to 80% of global terrestrial productivity, very little is known of the effects of UV on forest tree species. Only 15 tree species from North America have been screened for UV sensitivity and approximately half of those were found to be sensitive. Among the most sensitive species include loblolly, red and lodgepole pines. Preliminary evidence suggests that long lived plants such as trees can accumulate the damaging effects of UV radiation over many years. Therefore, even small, subtle changes which might not be significant during the first few years of growth, may continue to accumulate throughout the life of the tree. Due to the long lifespan of trees and the lengthy time required for breeding, forests may be particularly vulnerable to increases in UV resulting from ozone depletion.

Very little is known of the effects of UV on natural, nonagricultural ecosystems. To date, fewer than 60 species of native plants have been screened for UV sensitivity. However, some generalization can be made. Plants which have arisen from naturally high UV environments such as tropical mountains, are inherently more resistant to UV radiation, which suggests that these plants have evolved natural adaptations to repair or protect them from this damage. For example, one recent study of plants collected in Hawaii concluded that plants growing near sea level were much more sensitive to UV radiation than plants found growing near mountain tops. Due to this differential sensitivity, the biodiversity of natural ecosystems may be potentially altered. Experimental evidence from competition studies in the field indicates that UV radiation may alter the way in which plants interact and compete with one another without affecting their overall plant production. This, in turn, could also influence the biodiversity of natural ecosystems, with the more UV resistant plants replacing those which are more UV sensitive.

Although only limited information exists, there is evidence to suggest that exposure to UV radiation also may alter plant sensitivity to diseases, in some cases making plants much more susceptible to attack by pathogens. Other factors, such as

increases in carbon dioxide concentration and temperature which are also of interest with respect to global climate changes, have been shown to influence and modify the manner in which plants respond to increased UV radiation. For example, it has been demonstrated in rice, that the stimulating growth effect of carbon dioxide may not fully compensate all of the negative UV effects.

Even in the absence of further ozone depletion, the importance of present day levels of UV radiation has been demonstrated by experimentally reducing current, natural levels of solar UV radiation reaching plants. In these studies, growth and photosynthesis of bean seedlings has been altered by present day levels of solar UV. Whether these results are also true for mature plants has yet to be demonstrated, but these observations indicate the potential importance of solar UV radiation even without stratospheric ozone depletion.

Conclusions

1. **A large number of crops, native plants, and forest tree species may potentially be negatively impacted by increases in UV radiation.**
   - **some of these plants are directly sensitive to UV radiation**
   - **others may be indirectly affected by UV-induced increases in plant competition or disease susceptibility.**

2. **Due to the existence of genetic adaptations in our modern crops, breeders may be able to breed more UV-resistant crop plants in the future.**

3. **However, breeding is not an option for natural plant communities and forests, where increased UV may result in alterations in biodiversity.**

4. **Other global climate changes such as increased carbon dioxide or global warming may alter plant responses to UV (sometimes making the situation worse, other times making it better).**

5. **Plant research has been limited to only a few ongoing studies where plants are grown with realistic UV supplements, effectively prohibiting quantitative assessments or predictions now or in the future.**

6. **Present day levels of UV radiation can be damaging to plants even in the absence of ozone depletion.**

6

ENVIRONMENTAL EFFECTS OF OZONE DEPLETION

TESTIMONY OF

JAN C. VAN DER LEUN, Ph.D.
CHAIRMAN, UNEP PANEL ON ENVIRONMENTAL
EFFECTS OF OZONE DEPLETION

BEFORE THE

U.S. SENATE COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION

NOVEMBER 15, 1991

Mr. Chairman, members of the Committee, thank you for the opportunity to give my contribution to your hearing on ozone depletion and its impacts.

You asked me to give a brief summary of my background. I am Jan C. Van der Leun, Ph.D., Professor of Dermatology at the University of Utrecht, the Netherlands. My basic training was in physics. My main research interest became skin photobiology, the study of influences of light and ultraviolet radiation on human skin. This included the induction of skin cancer by ultraviolet radiation. Along this way I became involved in assessing the impacts of increased UV-B radiation to be expected as a consequence of depletion of the ozone layer. Presently I am chairman of the Panel on Environmental Effects of Ozone Depletion, formed by the United Nations Environment Programme.

The material I will report to you is based on the work of this Panel. My present testimony consists largely of the introduction and the executive summary of the Update-1991, just completed by the Panel. I take the opportunity to highlight a few of the key elements of this Update.

UV-B Radiation

Stratospheric ozone is the dominant factor limiting the penetration of solar UV-B radiation to the Earth's surface. This radiation is also limited by tropospheric ozone, aerosols and clouds. Pollution has increased the influence of the latter factors during the past decades. This is probably the reason some UV-B monitoring series showed a decrease of UV-B radiation while stratospheric ozone was also decreasing.

Clearcut increases of UV-B radiation were measured in both the Antarctic region during the presence of the ozone hole and in surrounding areas during the break-up of this hole. Decrease of UV-B radiation by pollution factors is probably mainly present in industrialized areas; most UV-B measurements are performed in these areas. There is no guarantee that these factors will continue to work in the same direction. Efforts to reduce pollution are underway, and in some cases they are beginning to have success. Climate change may also reduce cloudiness in certain areas. Such changes may bring out or even amplify the ozone-layer related increases of UV-B radiation; this would also occur in areas where these changes are masked now.

Human Health

Increase of skin cancer is still the effect for which the best quantitative predictions are possible. The Update-1991 gives a smaller number for the increase of non-melanoma skin cancer than the Report-1989. New experimental data show that this type of skin cancer is causedd not only by UV-B radiation but also, to some extent, by UV-A radiation, which is hardly influenced by atmospheric ozone. This makes the incidence less sensitive to ozone depletion.

Eye problems are expected to be at least as prevalent as discussed in the 1989 report. New investigations implicate UV-B radiation in more forms of cataract, a leading cause of blindness in the world.

UV-B radiation has profound influences on the immune system. Recent research confirms that these occur in man as well as in experimental animals. Skin pigmentation does not protect against these influences. There is concern that these effects might lead to an increase of infectious diseases; if this occurs, it will be so for people of all skin colors.

Food Supply

UV-B radiation, even at present levels, has a detrimental effect on many plants and aquatic organisms. This raises the concern that enhanced UV-B radiation may have a negative influence on world food production. The relationships between damage to individual organisms and the productivity of agriculture and fisheries are extremely complex. The scientific data available are by no means sufficient to make quantitative predictions in these areas.

Biodiversity

If enhanced UV-B radiation has a more negative effect on some species than on others, then the competitive balance in natural ecosystems may be shifted. There is concern that this may lead to a loss of species. Again, data are insufficient for precise predictions.

Research

For several potentially important effects, much more knowledge is needed to come to firm conclusions.

Thank you, Mr. Chairman.

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UNITED NATIONS
ENVIRONMENT PROGRAMME

ENVIRONMENTAL EFFECTS OF OZONE DEPLETION: 1991 UPDATE

Introduction
Executive Summary

Panel Report Pursuant to Article 6 of the Montreal Protocol on substances that Deplete the Ozone layer under the Auspices of the United Nations Environment Programme (UNEP)

November 1991

INTRODUCTION

ENVIRONMENTAL EFFECTS OF OZONE DEPLETION

The Montreal Protocol on Substances that Deplete the Ozone Layer requires in Article 6 periodic assessments of available scientific, environmental, technical and economic information. The assessments shall be made every four years.

The latest assessments were made in 1989. For the reconsideration of the agreements in the Montreal Protocol in 1992, UNEP decided that the 1989 assessments would be updated, rather than making completely new ones. The present report is such an update of the 1989 Environmental Effects Panel Report. It focuses, therefore, on developments since 1989. Information covered in the previous report that is still up-to-date is not repeated. For this reason, the chapters of this update include the summary of the corresponding chapter in the 1989 Report.

The occasion calls for an evaluation of how research on effects of increased UV-B radiation has proceeded during the past years. We cannot conceal that progress is disappointing. Many of the "Research Needs" formulated in previous reports have to be listed again. The scientific community has followed some of the recommendations, but by no means all. Urgent problems are still waiting to be addressed.

The underlying cause has been signalled over many years by the UNEP Co-ordinating Committee on the Ozone Layer. Funding for research on the consequences of increased UV-B radiation is disproportionately low, typically less than 1 percent of what is made available for atmospheric research in relation to ozone depletion. This comment is still valid. There is improvement of funding in some countries, but this is counterbalanced by a decrease in other countries. Several research groups, having contributed important information for previous assessments, have even ceased to exist. Effects research is necessary to provide policy makers with relevant information, so that they may evaluate response strategies to future challenges. The possibility to do this in a timely fashion may well depend on the funding situation.

Increased UV-B radiation will have many effects on man, animals, plants, and materials. For several potentially important effects, our Panel could do no more than express its concern; more knowledge is needed to come to firm conclusions. The deleterious effects that we recognize are serious enough to plea for action by the nations of the world to protect the ozone layer.

J.C. van der Leun
M. Tevini

EXECUTIVE SUMMARY

SOLAR INTERACTIONS

- Significant global scale decreases in total ozone have occurred over the past ten years.

- All other factors being constant, there is no scientific doubt that decreases in total ozone will increase UV-B radiation at ground level.

- Tropospheric ozone and aerosols may have masked the consequences of stratospheric ozone depletion for UV-B in some industrialized regions.

- It is likely that in areas remote from anthropogenic emissions, the UV-B changes due to stratospheric ozone depletion would be only partially compensated by tropospheric ozone and aerosol increases.

- There are no reliable estimates of the direction or magnitude of effects of any cloud cover trends on UV-B.

- Efforts to improve local and regional air quality may bring to light the increases in UV-B associated with the depletion of stratospheric ozone.

HEALTH

- The induction of immunosuppression by UV-B has now been demonstrated in humans, not only those of light pigmentation, but also deeply pigmented individuals.

  This places all of the world's populations at risk of the potential adverse impacts of UV-B on the immune system, including possible increases in the incidence or severity of infectious disease.

- An increased number of adverse ocular effects have been associated with exposure to UV. These include age-related nearsightedness, deformation of the lens capsule, and nuclear cataract (a form of cataract which previous information excluded from consideration). These effects appear to be independent of pigmentation. Including nuclear cataract among the forms of cataract likely to increase with ozone depletion enlarges slightly the risk estimates. It is now predicted that, all other things being equal, a sustained 10% decrease in ozone will be associated with between 1.6 and 1.75 million additional cases of cataract per year world-wide.

- Recent information on the relationship of non-melanoma skin cancer to UV exposures confirms previous findings and has allowed refinement of the carcinogenic action spectrum. Incorporation of this new information into the risk estimation process has led to slightly lower predictions. It is now predicted that a sustained 10% decrease in ozone will be associated with a 26% increase in non-melanoma skin cancer. All other things remaining

constant, this would mean an increase in excess of 300,000 cases per year worldwide.

TERRESTRIAL PLANTS

- Continued research on plant responses to UV-B radiation underscores the concern for agriculture, forestry, and natural ecosystems as the ozone layer is depleted.

- Growth and photosynthesis of certain plants (e.g., seedlings of rye, maize, and sunflower) can be inhibited even under ambient levels of UV-B radiation.

- Certain environmental factors, both biotic (e.g., plant diseases and competition with other plants) and abiotic (e.g., carbon dioxide, temperature, heavy metals, and water availability), can interact with the effect of UV-B radiation in plants. This makes it difficult to make quantitative predictions.

- Although most research to date has been with plants from temperate regions, data also show that certain tropical species may be adversely affected by enhanced UV-B radiation.

AQUATIC ECOSYSTEMS

- Marine phytoplankton produces at least as much biomass as all terrestrial ecosystems combined.

- Recent results show that the aquatic ecosystem is already under UV-B stress and there is concern that an increase in UV-B radiation will cause detrimental effects.

- One consequence of losses in phytoplankton is reduced biomass production which is propagated throughout the whole food web. This may result in losses of biomass for human consumption.

- The marine phytoplankton is a major sink for atmospheric carbon dioxide. Any reduction of the populations would decrease the uptake of carbon dioxide and so augment the greenhouse effect. Also, phytoplankton production of DMS (dimethylsulphate), which acts as a precursor of cloud nucleation, would be reduced, hence potentially affecting global climate.

- A UV-B induced decrease in microorganisms fixing atmospheric nitrogen would require significant substitution by artificial fertilizers, e.g., in rice production.

TROPOSPHERIC AIR QUALITY

- Chemical reactivity in the troposphere is expected to increase in response to increases in UV-B.

- Tropospheric ozone concentrations could rise in moderate to heavily polluted areas, but should decrease in unpolluted regions (with low oxides of nitrogen levels), as recently

confirmed by measurements in the Antarctic.

- Other potentially harmful substances (hydrogen peroxide, acids, and aerosols) are expected to increase in all regions of the troposphere due to the enhanced chemical reactivity.

- These changes could exacerbate problems of human health and welfare, increase damage to the biosphere, and might make current air quality goals more difficult and expensive to attain.

MATERIALS DAMAGE

- UV-B radiation is particularly effective in light-induced degradation of wood and plastic products, leading to discoloration, and loss of strength. Increased UV-B content in sunlight will cause more rapid degradation, resulting in increased costs of using higher levels of conventional light stabilizers, possible design of new stabilizers, and faster replacement of the affected products.

- Available research data are inadequate to reliably estimate the damage from higher UV-B levels to materials. Very limited relevant data are available for important classes of materials such as wood, plastic coatings, plastics used outdoors, and rubber. Data pertaining to performance of plastics in near-equator regions of the world, with the harshest exposure environments, are particularly needed.

- Some on-going work relating to exposure of plastics under desert conditions is likely to contribute some of the needed data within the next few years. This may lead to improved assessment of damage to plastics resulting from partial ozone depletion, at that time.

KEY AREAS OF UNCERTAINTY

The key areas of uncertainty are the following:

- Quantification of the primary effects on food production and quality, on forestry, and on natural ecosystems.

- Clarification and quantification of influences on human health, especially the immune system, and occurrences of melanomas and cataracts.

- Effects on biota of the enhanced UV radiation during the Antarctic springtime ozone depletion.

The report on Environmental Effects of Ozone Depletion *was prepared by an international group of scientists. The chairman of the group was Dr. Jan C. van der Leun (The Netherlands), and the co-chairman was Dr. Manfred Tevini (Federal Republic of Germany).*

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Executive Summary
Scientific Assessment of Stratospheric Ozone, 1991

22 October 1991

Executive Summary: Scientific Assessment of Stratospheric Ozone, 1991

22 October 1991

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Recent Major Scientific Findings

Over the past few years, there have been highly significant advances in the understanding of the impact of human activities on the Earth's stratospheric ozone layer and the influence of changes in chemical composition on the radiative balance of the climate system. Specifically, since the last international scientific review (1989), there have been five major advances:

- **Global Ozone Decreases:** Ground-based and satellite observations continue to show decreases of total column ozone in winter in the northern hemisphere. For the first time, there is evidence of significant decreases in *spring and summer* in both the northern and southern hemispheres at middle and high latitudes, as well as in the southern winter. No trends in ozone have been observed in the tropics. These downward trends were larger during the 1980s than in the 1970s. The observed ozone decreases have been occurred predominantly in the *lower* stratosphere.

- **Polar Ozone:** Strong Antarctic ozone holes have continued to occur and, in four of the past five years, have been deep and extensive in area. This contrasts to the situation in the mid-1980s, where the depth and area of the ozone hole exhibited a quasi-biennial modulation. Large increases in surface ultraviolet radiation have been observed in Antarctica during periods of low ozone. While no extensive ozone losses have occurred in the Arctic comparable to those observed in the Antarctic, localized Arctic ozone losses have been observed in winter concurrent with observations of elevated levels of reactive chlorine.

- **Ozone and Industrial Halocarbons:** Recent laboratory research and re-interpretation of field measurements have strengthened the evidence that the Antarctic ozone hole is primarily due to chlorine- and bromine-containing chemicals. In addition, the weight of evidence suggests that the observed middle- and high-latitude ozone losses are largely due to chlorine and bromine. Therefore, as the atmospheric abundances of chlorine and bromine increase in the future, significant additional losses of ozone are expected at middle latitudes and in the Arctic.

- **Ozone and Climate Relations:** For the first time, the observed global lower-stratospheric ozone depletions have been used to calculate the changes in the radiative balance of the atmosphere. The results indicate that, over the last decade, the observed ozone depletions would have tended to cool the lower stratosphere at middle and high latitudes. Temperature data suggest that some cooling indeed has taken place there. The observed lower-stratospheric ozone changes and calculated temperature changes would have caused a decrease in the radiative forcing of the surface-troposphere system in the middle- to high-latitudes that is larger in magnitude than that predicted for the CFC increases over the last decade. In addition, the ozone depletion may indeed have offset a significant fraction of the radiative forcing due to increases of all greenhouse gases over the past decade.

- **Ozone Depletion and Global Warming Potentials (ODPs and GWPs):** A new semi-empirical, observation-based method of calculating ODPs has better quantified the role of polar processes in this index. In addition, the direct GWPs for tropospheric, well-mixed, radiatively active species have been recalculated. However, because of the incomplete understanding of tropospheric chemical processes, the indirect GWP of methane has not, at present, been quantified reliably. Furthermore, the concept of a GWP may prove inapplicable for the very short-lived, inhomogeneously mixed gases, such as the nitrogen oxides. Hence, many of the *indirect* GWPs reported in 1990 by the Intergovernmental Panel on Climate Change (IPCC) are likely to be incorrect.

Supporting Evidence and Related Issues

Global Ozone

- Independent observations from the ground-based Dobson and M-83/124 instruments and the TOMS satellite instrument all show, for the first time, that there are significant decreases in total-column ozone, after accounting for known natural variability, in winter and now in spring and summer in both the northern and southern hemispheres at middle and high latitudes, but not in the tropics. The following table illustrates some of these points.

Total Ozone Trends (% per decade with 95% confidence limits)

	TOMS: 1979-91			Ground-based: 26°N - 64°N	
Season	45°S	Equator	45°N	1979-1991	1970-1991
Dec-Mar	-5.2 ± 1.5	+0.3 ± 4.5	-5.6 ± 3.5	-4.7 ± 0.9	-2.7 ± 0.7
May-Aug	-6.2 ± 3.0	+0.1 ± 5.2	-2.9 ± 2.1	-3.3 ± 1.2	-1.3 ± 0.4
Sep-Nov	-4.4 ± 3.2	+0.3 ± 5.0	-1.7 ± 1.9	-1.2 ± 1.6	-1.2 ± 0.6

- There is strong *combined* observational evidence from balloonsondes, ground-based Umkehr, and the SAGE satellite instruments that, over the past decade, annual-average ozone has decreased in the middle- and high-latitude stratosphere below 25 km (about 10% near 20 km).

- Ozone losses in the upper stratosphere have been observed by ground-based Umkehr and SAGE satellite instruments. Changes in the shape of the vertical distribution of ozone near 40 km are qualitatively consistent with theoretical predictions, but are smaller in magnitude.

- Measurements indicate that ozone levels in the troposphere up to 10 km above the few existing balloonsonde stations at northern middle latitudes have increased by about 10% per decade over the past two decades. However, the data base for ozone trends in the upper troposphere, where it is an effective greenhouse gas, are sparse and inadequate for quantifying its contribution to the global radiative balance. It should be noted that the response of ozone in the upper troposphere is particularly sensitive to oxides of nitrogen injected by aircraft.

- The temperature record indicates that a small cooling (about 0.3°C per decade, globally averaged) has occurred in the lower stratosphere over the last two decades, which is in the sense of that expected from the observed ozone change.

- Increases continue in the atmospheric abundances of source gases that affect ozone and the radiative balance. Although methane has continued to increase in the atmosphere, the rate of increase has slowed, for reasons that are not understood. Methyl bromide is the major contributor to stratospheric bromine (15 pptv). The sources of methyl bromide are not well characterized; however, significant anthropogenic emissions have been suggested.

• Recent laboratory studies have identified key heterogeneous reactions and have allowed a more-quantitative assessment of the role of global stratospheric sulfate aerosols in leading to enhanced abundances of reactive chlorine species.

• Limited observations suggest that the abundance of chlorine monoxide (ClO) in the lower stratosphere at northern middle latitudes is greater than that predicted by models containing only currently known gas-phase chemistry, and the observed seasonal and latitudinal dependences are inconsistent with those predicted. Some new studies that incorporate currently known heterogeneous processes provide an improved simulation for some observed gases, such as ClO and nitric acid.

• Present models containing only gas-phase processes cannot simulate the observed seasonal ozone depletions at middle and high latitudes. However, models incorporating currently known heterogeneous processes on sulfate aerosols predict substantially greater ozone depletion (e.g., a factor of 2 - 3 at middle latitudes) from chlorine and bromine compounds compared to models containing only gas-phase processes. Indeed, the heterogeneous models simulate most of the observed trend of column ozone in middle latitudes in summer, but only about half of that in winter.

• There is not a full accounting of the observed downward trends in global ozone. Plausible mechanisms include (i) local heterogeneous chemistry on stratospheric sulfate aerosols (as evidenced by, for example, elevated levels of ClO and the presence of sulfate aerosols at the altitudes of the observed ozone depletion) and (ii) the transport of both ozone-depleted and chemically perturbed polar air to middle latitudes (as evidenced by high levels of reactive chlorine and low levels of reactive nitrogen, which is a characteristic of chemically perturbed polar air). Although other possible mechanisms cannot be ruled out, those involving chlorine and bromine appear to be largely responsible for the ozone loss and are the only ones for which direct evidence exists.

• Since the middle latitude ozone losses are apparently due in large part to chlorine and bromine, greater ozone losses are expected as long as the atmospheric levels of these compounds continue to increase. With the increases in the levels of chlorine and bromine that are estimated for the year 2000, the additional ozone losses during the 1990s are expected to be comparable to those already observed for the 1980s.

• There are numerous ways in which further increases in stratospheric halogen abundances can be reduced. The table below illustrates the effects of reducing the emissions of several types of halocarbons. Four aspects are shown: (i) the change in peak chlorine loading, (ii) the times at which chlorine abundances have decreased back to 2 ppbv (the abundance in the late 1970s, which is when the Antarctic ozone hole started and when the accelerated trends in total-column ozone losses in the northern hemisphere began); (iii) the times at which chlorine abundances have decreased back to 3 ppbv (the abundance in the mid-to-late 1980s); and (iv) a measure of the cumulative ozone loss for the time period that the chlorine levels are above 3 ppbv. All of the values in the table are relative to the reference scenario (AA).

Scenarios for Reducing Chlorine Emissions

Scenario	Peak Cl (ppbv)	Year at 3 ppbv	Year at 2 ppbv	Integral (Cl>3 ppbv)
AA	**4.1 (ppbv)**	**2027**	**2060**	**22.7 ppbv-yr**
AA3	-0.18	-10 yrs	-7 yrs	-7.6
D	-0.03	0	0	-1.3
D3	-0.10	0	0	-2.9
E	0.00	-7	-3	-2.0 *
E3	-0.03 *	-10	-3	-4.4 *
F20	+0.01	0	0	+0.8
F40	+0.02	+1	0	+1.5
G20	+0.01	+5	+2	+4.2
AA3 + D3	-0.21	-11	-7	-10.4

* These values should be reduced by a factor of about 2 - 3 when evaluating ozone loss rather than chlorine loading.

- Definitions of scenarios:

AA: Montreal Protocol (10 yr lag of 10% of CFCs plus CCl_4; no lag for CH_3CCl_3 and Halons). HCFC-22 increases at 3% per year from 1991 to 2020, ramps to 0 by 2040. No substitution of CFCs with HCFCs.

o Non-substitution scenarios:
AA3: 3 year acceleration of CFCs and CCl_4 schedules.
D: 3 year acceleration of CH_3CCl_3 schedule.
D3: CH_3CCl_3 on the accelerated CFC phase-out schedule.
E: HCFC-22 ramp to zero between 2000 and 2020.
E3: HCFC-22 on the accelerated CFC phase-out schedule.

o Substitution scenarios:
HCFC substitutions begin in 1995, no growth to 2000, 3% per year to 2020, ramp to zero by 2030. HCFC-A has a 2 year lifetime, one chlorine, and an ODP of 0.013. HCFC-B has a 20 year lifetime, one chlorine, and an ODP of 0.13.
F20: 20% initial substitution, HCFC-A.
F40: 40% initial substitution, HCFC-A.
G20: 20% initial substitution, HCFC-B.

• Stratospheric bromine is 30 - 120 times more efficient than stratospheric chlorine in destroying ozone on a per atom basis. Therefore, 1 pptv of stratospheric bromine is equivalent to 0.03 - 0.12 ppbv of stratospheric chlorine.

Polar Ozone

• The Antarctic ozone hole in 1991 was as deep and as extensive in area as those of 1987, 1989, and 1990. The low value of total-column ozone measured by TOMS in early October in 1991 was 110 Dobson units, which is a decrease of about 60% compared to the ozone levels prior to the late 1970s. The previously noted quasi-biennial modulation of the severity of the ozone hole did not occur during the past three years. This apparent lack of variability in recent years may imply that halocarbon chemistry is becoming dominant over dynamically induced fluctuations of Antarctic ozone depletion.

• Recent laboratory studies of heterogeneous processes, reevaluated field measurements, and modeling studies have strengthened the confidence that the cause of the Antarctic ozone hole is primarily chlorine and bromine emissions.

• High concentrations of ClO have been observed in winter in the Arctic stratosphere between 16 -20 km. These observations have been incorporated into diagnostic models that have calculated localized ozone depletions of about 10% at these altitudes over a period of about a month, which are consistent with concurrent ozone measurements.

Ozone/Climate Relations

• The ozone losses observed in the lower stratosphere over the last decade are predicted to have increased the visible and ultraviolet incoming solar radiation reaching the surface/troposphere system and decreased the downward infrared radiation reaching the surface/troposphere system. For models that allow for the temperature of the stratosphere to adjust to the loss of ozone, the net effect is a decrease in radiative forcing. For middle and high latitudes throughout the year, the magnitude of this decrease may be larger than the predicted increases in the radiative forcing due to the increased abundances of CFCs over the last decade. Indeed, this ozone-induced decrease in radiative forcing could be offsetting a significant fraction of the increased forcing attributed to the increases in the abundances of all greenhouse gases over the same period. Changes in the global annual-average radiative forcing due to the observed ozone depletion are predicted to be comparable in magnitude, but opposite in sign, to those attributed to the CFCs over the last decade.

• Current tropospheric models exhibit large differences in their predictions of changes in ozone, the hydroxyl radical, and other chemically active gases due to emissions of methane, nonmethane hydrocarbons, carbon monoxide, and nitrogen oxides. This arises from uncertainties in the knowledge of background chemical composition and an inadequate understanding of chemical reactions and dynamical processes. Hence, these deficiencies limit the accuracy of predicted changes in the abundance and distribution of tropospheric ozone, which is a greenhouse gas, and in the lifetimes of a number of other greenhouse gases, including the HCFCs and HFCs, which depend upon the abundance of the hydroxyl radical.

Ozone Depletion and Global Warming Potentials (ODPs and GWPs)

- Steady-state and time-dependent ODPs have been recalculated with improved models that have incorporated more-accurate reaction rate coefficients and absorption cross sections and known heterogeneous processes on sulfate aerosols. The numerical values are generally similar to those in previous assessments.

- A new semi-empirical, observation-based method of calculating ODPs has been developed. The resulting values are generally larger (up to a factor of two as compared to some model-based estimates) for species with long stratospheric lifetimes (e.g., HCFC-22 and HCFC-142b) and slightly smaller for species with short stratospheric lifetimes (e.g., carbon tetrachloride and methyl chloroform). Since this approach utilizes more atmospheric observations and less model calculations in characterizing polar ozone losses, it is considered to be better than standard model ODPs, at least in the polar regions.

- The *direct GWPs* (with five different time horizons: 20, 50, 100, 200, and 500 years) for tropospheric, well-mixed, radiatively active species have been recalculated using updated lifetimes for methane, nitrous oxide, and the halocarbons and following the same methodology of IPCC (1990). With the exception of methane, new GWP results indicate only modest changes from the IPCC values, but uncertainties still exist in these calculations due to limitations in knowledge of the carbon cycle.

- Because of incomplete understanding of tropospheric chemical processes, the *indirect GWP* of methane has not been quantified reliably at the time of this report, although improvements and quantifications of uncertainties in the near future are highly likely. The signs of the net changes in radiative forcing from known indirect effects have been established for some of the trace gases: methane, carbon monoxide, and nonmethane hydrocarbons, which are all positive. The sign of the changes in radiative forcing due to the nitrogen oxides cannot currently be established. Furthermore, the basic concept of a GWP may indeed prove to be inapplicable for the very short-lived, inhomogeneously mixed gases, such as the nitrogen oxides and the nonmethane hydrocarbons. Hence, the IPCC (1990) *indirect* GWPs are not only uncertain, but many are also likely to be incorrect (e.g., for the nitrogen oxides).

Related Issues

- Ultraviolet radiation. Significant increases in ultraviolet radiation have been observed over Antarctica in conjunction with periods of intense ozone depletion. Under clear-sky conditions, these increases are consistent with theoretical predictions. Furthermore, a Erythemal Radiative Amplification Factor of 1.25 ± 0.20 has been deduced from simultaneous measurements of column ozone and surface ultraviolet radiation at a clean air site, which is in agreement with a model-calculated value of 1.1. Therefore, for the first time, the response of ground-level ultraviolet radiation to changes in column ozone has been observed and quantified.

- Supersonic aircraft. A previous, independent assessment of the impact of a projected fleet of supersonic aircraft on stratospheric ozone has reported the prediction that the ozone loss increases with the amount of nitrogen oxides emitted. These models used gas-phase chemistry and assessed ozone loss for the case of 500 aircraft flying at Mach 2.4 between 17 - 20 km with an annual fuel use of 7×10^{10} kg/yr. The annual-average loss of column ozone at middle latitudes in the northern hemisphere is predicted to be 2 - 6%. For a comparable fleet operated at Mach 3.2 between 21 - 24 km, the comparable column ozone losses are 7 - 12%. However, recent evidence has shown that reactions on sulfate aerosols

can change the partitioning of nitrogen oxides. Two model studies incorporating this heterogeneous chemistry have recently reexamined the Mach 2.4 case and found substantially less ozone change (-0.5% to +0.5%). These implications are being examined as part of a separate assessment.

• Shuttles and rockets. The increase in the abundance of stratospheric chlorine from one projection of U. S. annual launches of nine Space Shuttles and six Titan rockets is calculated to be less than 0.25% of the annual stratospheric chlorine source from halocarbons in the present day atmosphere (with maximum increases of 0.01 ppbv in the middle and upper stratosphere in the northern middle and high latitudes). The TOMS ozone record shows no detectable changes in column ozone immediately following each of several launches of the Space Shuttle.

• Volcanoes, ozone loss, and climate perturbations. Major volcanic eruptions, such as Mt. Pinatubo, substantially increase the stratospheric abundance of sulfate aerosols for a few years. Since laboratory and field data show that heterogeneous processes can lead to increased levels of reactive chlorine in the stratosphere, such injections have the potential to increase ozone losses temporarily. Furthermore, the increased levels of stratospheric sulfate aerosols are predicted to warm the lower stratosphere by about 4°C (which has been observed) and cool the Earth's surface by a much smaller amount.

• Tropospheric sulfate aerosols and climate. Fossil fuel emissions over the past century have increased the tropospheric sulfate aerosol concentrations. Their contribution to the direct radiative forcing of the clear-sky northern hemisphere is opposite to that due to the greenhouse gases and is estimated to be a substantial fraction of the trace gas forcing.

Implications for Policy Formulations

The findings and conclusions of the research of the past few years have several major implications as input to policy decisions regarding human-influenced substances that lead to stratospheric ozone depletions and to changes in the radiative forcing of the climate system:

• **Continued global ozone losses:** Even if the control measures of the amended Montreal Protocol (London, 1990) were to be implemented by all nations, the current abundance of stratospheric chlorine (3.3 - 3.5 ppbv) is estimated to increase during the next several years, reaching a peak of about 4.1 ppbv around the turn of the century. With these increases, the additional middle-latitude ozone losses during the 1990s are expected to be comparable to those observed during the 1980s, and there is the possibility of incurring wide-spread losses in the Arctic. *Reducing these expected and possible ozone losses requires further limitations on the emissions of chlorine- and bromine-containing compounds.*

• **Approaches to lowering global risks:** Lowering the peak and hastening the subsequent decline of chlorine and bromine levels can be accomplished in a variety of ways, including an accelerated phase-out of controlled substances and limitations on currently uncontrolled halocarbons. Chlorine. A significant reduction in peak chlorine loading (a few tenths of a ppbv) can be achieved with accelerated phase-out schedules of CFCs, carbon tetrachloride, and methyl chloroform. Even stringent controls on HCFC-22 would not significantly reduce peak chlorine loading (at most 0.03 ppbv, especially when ODP weighted), but do hasten the decline of chlorine. Bromine. A 3-year acceleration of the phase-out schedule for the Halons would reduce peak bromine loading by about 1 pptv. If the anthropogenic sources of methyl bromide are significant and their emissions can be reduced, then *each* 10% reduction in methyl bromide would rapidly result in a decrease in stratospheric bromine of 1.5 pptv, which is equivalent to a reduction

in chlorine of 0.045 to 0.18 ppbv. This gain is comparable to that of a three-year acceleration of the scheduled phase-out of the CFCs.

• **Elimination of the Antarctic ozone hole:** The phase-out schedule of the amended Montreal Protocol, *if fully complied by all nations* and if there are no *continued* uses of HCFCs, affords the opportunity to return to stratospheric chlorine abundances of 2 ppbv sometime between the middle and the end of the next century. This is the level at which the Antarctic ozone hole appeared in the late 1970s and hence is about the level that is thought to be necessary (other conditions assumed constant, including bromine loading) to eliminate the ozone hole. *Such levels could never have been reached under the provisions of the original Protocol (Montreal, 1987).*

• **Uncertain greenhouse role of CFCs:** The weight of evidence suggests that a large part of the observed lower stratospheric decrease in ozone is the result of CFC emissions. Furthermore, the radiative impact of this ozone decrease may have largely offset the predicted direct radiative perturbations, at middle to high latitudes, due to the CFCs increases over the last decade. *Hence, even the sign of the overall radiative effect of CFC increases on the climate system over the last decade is uncertain.*

• **Utility of GWPs:** The direct GWPs are a useful indicator of the relative radiative effects of long-lived, well-mixed, radiatively active trace species. However, GWPs may be inapplicable for comparing the direct radiative effects of a long-lived, well-mixed gas to the indirect effects of a short-lived gas (for example, carbon dioxide to the nitrogen oxides). *For the latter need, the application of new tools, such as three-dimensional, fully coupled coupled chemistry-climate models may be required.*

NASA

National Aeronautics and Space Administration

Testimony
Presented by Witness

November 15, 1991

Committee on Commerce, Science and Transportation

United States Senate

Statement by:
Robert T. Watson
Director, Process Studies Program
Earth Science and Applications Division

102nd Congress

Statement of

Dr. Robert T. Watson

Earth Science and Applications Division

Office of Space Science and Applications

National Aeronautics and Space Administration

before the

Committee on Commerce, Science, and Transportation

United States Senate

Mr. Chairman and Members of the Committee:

I am pleased to be here to discuss the issue of ozone depletion. The dramatic rise in world population and industrial activities during the last century have produced the concern that human activities are affecting the global environment. In particular, there are two inter-related global environment changes, i.e., atmospheric ozone depletion and global warming, that may effect both human well being and the quality of life. Ozone depletion is primarily caused through the emissions of anthropogenic chlorine and bromine containing chemicals into the atmosphere, while global warming is predicted to occur as a result of increasing atmospheric concentrations of radiatively active trace gases such as carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and tropospheric ozone. These environmental issues are no longer the sole concern of the scientific community and environmental groups, and their importance has now been recognized by governments around the world.

The current concern over ozone depletion has resulted in the endorsement, at the highest levels of governments, for regular comprehensive scientific, environmental impacts, technical and economic assessments to be performed. Three state-of-the-art assessments were conducted in response to the mandate of the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol on Substances that Deplete the Ozone Layer. These assessments included: (i) an assessment of our understanding of the processes controlling the present distribution and rate of change of atmospheric ozone; (ii) an assessment of the environmental impacts of ozone depletion; and (iii) an assessment of the technological feasibility and economic costs associated with the substitution of substances controlled under the Montreal Protocol. The scientific assessment was co-chaired by Dr. Albritton of NOAA and myself; the impacts assessment was co-chaired by Dr Jan van der Leun of the Netherlands and Dr. Manfred Tevini of Germany; and the technology/economics assessment was co-chaired by Dr. Stephen Lee-Bapty of the U.K. and Dr. Stephen Anderson of U.S. EPA.

My testimony today will briefly discuss the key findings of the 1991 International Scientific Assessment of Ozone Depletion with respect to the extent and cause of ozone depletion and possible approaches to minimize future ozone depletion. Dr. Daniel Albritton will address the climate implications of these findings. The executive summary of the scientific assessment is presented verbatim in the Appendix to this testimony.

Key Findings:

Observational Record: Since the 1989 assessment the observational record includes an additional 2.5 years of Dobson, SAGE, and TOMS data and a complete re-analysis of 29 ground-

based M-83/124 stations in the USSR. This is complemented by a major new advance in the observational record of an internally calibrated TOMS data set that is now independent of ground-based observations. Trend analyses of SAGE data have been extended to the lower stratosphere and the Umkehr data have been reanalyzed.

Antarctic Ozone: The Antarctic ozone hole in 1991 was as deep and as extensive in area as those of 1987, 1989, and 1990. The low value of total ozone measured in 1991 was 110 Dobson Units, a decrease of 60% compared to ozone levels prior to the late 1970s. The previously noted quasi-biennial modulation of the severity of the ozone hole did not occur during the last three years. The area of the ozone hole was similar for these 4 years.

Trends in Total Ozone: Ground-based (Dobson and M-83/124) and satellite (TOMS) observations of total column ozone through March 1991 were analyzed allowing for the influence of solar cycle and quasi-biennial oscillation (see table). They show that:

(a) the northern mid-latitude winter and summer decreases during the 1980s were larger than the average trend since 1970 by about 2% /decade. A significant longitudinal variance of the trend since 1979 is observed.

(b) for the first time there are statistically significant decreases in all seasons in both the northern and southern hemispheres at mid- and high-latitudes during the 1980s; the northern mid-latitude long-term trends (1970-91), while smaller, are also statistically significant in all seasons.

(c) there has been no statistically significant decrease in tropical latitudes from 25°N to 25°S.

Total Ozone Trends in %/decade with 95% confidence limits

	TOMS: 1979-1991			Ground-based: 26°N - 64°N	
	45°S	Equator	45°N	1979-1991	1970-1991
Dec-Mar	-5.2 ± 1.5	+0.3 ± 4.5	-5.6 ± 3.5	-4.7 ± 0.9	-2.7 ± 0.7
May-Aug	-6.2 ± 3.0	+0.1 ± 5.2	-2.9 ± 2.1	-3.3 ± 1.2	-1.3 ± 0.4
Sep-Nov	-4.4 ± 3.2	+0.3 ± 5.0	-1.7 ± 1.9	-1.2 ± 1.6	-1.2 ± 0.6

Trends in the Vertical Distribution of Ozone: Balloonsonde, ground-based Umkehr, and satellite SAGE observations show that:

(a) ozone is decreasing in the lower stratosphere, i.e., below 25 km, at about 10%/decade, consistent with the observed decrease in column ozone.

(b) changes in the observed vertical distribution of ozone in the upper stratosphere near 40 km are qualitatively consistent with theoretical predictions, but are smaller in magnitude.

(c) measurements indicate that ozone levels in the troposphere, over the few existing ozone sounding stations at northern mid-latitudes, have increased about 10%/decade over the past 2 decades.

Ultraviolet radiation: Significant increases in ultraviolet radiation have been observed over Antarctica in conjunction with periods of intense ozone depletion. Under clear-sky conditions, these increases are consistent with theoretical predictions. Therefore, for the first time, the response of ground-level ultraviolet radiation to changes in column ozone has been observed and quantified.

Cause of the Observed Ozone Depletion: Recent laboratory research and re-interpretation of field measurements have strengthened the evidence that the Antarctic ozone hole is primarily due to chlorine- and bromine-containing chemicals. In addition, the weight of evidence suggests that the observed middle- and high-latitude ozone losses are largely due to chlorine and bromine.

Future Levels of Ozone Depletion: Even if the control measures of the amended Montreal Protocol (London, 1990) were to be implemented by all nations, the current abundance of stratospheric chlorine (3.3 - 3.5 parts per billion volume (ppbv)) is estimated to increase during the next several years, reaching a peak of about 4.1 ppbv around the turn of the century. Since the middle latitude ozone losses are apparently due in large part to chlorine and bromine, the increased levels of chlorine and bromine that are estimated by the year 2000 are expected to result in additional ozone losses during the 1990s comparable to those already observed for the 1980s. There is also the possibility of incurring wide-spread losses in the Arctic. Reducing these expected and possible ozone losses requires further limitations on the emissions of chlorine- and bromine-containing compounds.

Approaches to Limiting Future Levels of Ozone Depletion: Lowering the peak chlorine loading by a few tenths of a ppbv and the peak bromine loading by about 1 parts per trillion by volume (pptv), and hastening the subsequent decline of chlorine and bromine levels can be accomplished in a variety of ways, including accelerating all regulatory steps on controlled substances (CFCs, carbon tetrachloride, methyl chloroform, and Halons) by about 3 years and limitations on currently uncontrolled halocarbons (e.g., HCFC-22). It should also be noted that if the anthropogenic sources of methyl bromide are significant and their emissions can be reduced, then *each* 10% reduction in methyl bromide would rapidly result in a decrease in stratospheric bromine of 1.5 pptv, which is equivalent to a reduction in stratospheric chlorine of 0.045 to 0.18 ppbv. This gain is comparable to that of a three-year acceleration of the scheduled phase-out of the CFCs.

APPENDIX

Executive Summary of the Scientific Assessment of Ozone Depletion

Recent Major Scientific Findings

Over the past few years, there have been highly significant advances in the understanding of the impact of human activities on the Earth's stratospheric ozone layer and the influence of changes in chemical composition on the radiative balance of the climate system. Specifically, since the last international scientific review (1989), there have been five major advances:

- **Global Ozone Decreases:** Ground-based and satellite observations continue to show decreases of total column ozone in winter in the northern hemisphere. For the first time, there is evidence of significant decreases in *spring and summer* in both the northern and southern hemispheres at middle and high latitudes, as well as in the southern winter. No trends in ozone have been observed in the tropics. These downward trends were larger during the 1980s than in the 1970s. The observed ozone decreases have occurred predominantly in the *lower* stratosphere.

- **Polar Ozone:** Strong Antarctic ozone holes have continued to occur and, in four of the past five years, have been deep and extensive in area. This contrasts to the situation in the mid-1980s, where the depth and area of the ozone hole exhibited a quasi-biennial modulation. Large increases in surface ultraviolet radiation have been observed in Antarctica during periods of low ozone. While no extensive ozone losses have occurred in the Arctic comparable to those observed in the Antarctic, localized Arctic ozone losses have been observed in winter concurrent with observations of elevated levels of reactive chlorine.

- **Ozone and Industrial Halocarbons:** Recent laboratory research and re-interpretation of field measurements have strengthened the evidence that the Antarctic ozone hole is primarily due to chlorine- and bromine-containing chemicals. In addition, the weight of evidence suggests that the observed middle- and high-latitude ozone losses are largely due to chlorine and bromine. Therefore, as the atmospheric abundances of chlorine and bromine increase in the future, significant additional losses of ozone are expected at middle latitudes and in the Arctic.

- **Ozone and Climate Relations:** For the first time, the observed global lower-stratospheric ozone depletions have been used to calculate the changes in the radiative balance of the atmosphere. The results indicate that, over the last decade, the observed ozone depletions would have tended to cool the lower stratosphere at middle and high latitudes. Temperature data suggest that some cooling indeed has taken place there. The observed lower-stratospheric ozone changes and calculated temperature changes would have caused a decrease in the radiative forcing of the surface-troposphere system in the middle- to high-latitudes that is larger in magnitude than that predicted for the CFC increases over the last decade. In addition, the ozone depletion may indeed have offset a significant fraction of the radiative forcing due to increases of all greenhouse gases over the past decade.

- **Ozone Depletion and Global Warming Potentials (ODPs and GWPs):** A new semi-empirical, observation-based method of calculating ODPs has better quantified the role of polar processes in this index. In addition, the direct GWPs for tropospheric, well-mixed, radiatively active species have been recalculated. However, because of the

incomplete understanding of tropospheric chemical processes, the indirect GWP of methane has not, at present, been quantified reliably. Furthermore, the concept of a GWP may prove inapplicable for the very short-lived, inhomogeneously mixed gases, such as the nitrogen oxides. Hence, many of the *indirect* GWPs reported in 1990 by the Intergovernmental Panel on Climate Change (IPCC) are likely to be incorrect.

Supporting Evidence and Related Issues

Global Ozone

- Independent observations from the ground-based Dobson and M-83/124 instruments and the TOMS satellite instrument all show, for the first time, that there are significant decreases in total-column ozone, after accounting for known natural variability, in winter and now in spring and summer in both the northern and southern hemispheres at middle and high latitudes, but not in the tropics. The following table illustrates some of these points.

Total Ozone Trends (% per decade with 95% confidence limits)

	TOMS: 1979-91			Ground-based: 26°N - 64°N	
Season	45°S	Equator	45°N	1979-1991	1970-1991
Dec-Mar	-5.2 ± 1.5	+0.3 ± 4.5	-5.6 ± 3.5	-4.7 ± 0.9	-2.7 ± 0.7
May-Aug	-6.2 ± 3.0	+0.1 ± 5.2	-2.9 ± 2.1	-3.3 ± 1.2	-1.3 ± 0.4
Sep-Nov	-4.4 ± 3.2	+0.3 ± 5.0	-1.7 ± 1.9	-1.2 ± 1.6	-1.2 ± 0.6

- There is strong *combined* observational evidence from balloonsondes, ground-based Umkehr, and the SAGE satellite instruments that, over the past decade, annual-average ozone has decreased in the middle- and high-latitude stratosphere below 25 km (about 10% near 20 km).

- Ozone losses in the upper stratosphere have been observed by ground-based Umkehr and SAGE satellite instruments. Changes in the shape of the vertical distribution of ozone near 40 km are qualitatively consistent with theoretical predictions, but are smaller in magnitude.

- Measurements indicate that ozone levels in the troposphere up to 10 km above the few existing balloonsonde stations at northern middle latitudes have increased by about 10% per decade over the past two decades. However, the data base for ozone trends in the upper troposphere, where it is an effective greenhouse gas, are sparse and inadequate for quantifying its contribution to the global radiative balance. It should be noted that the response of ozone in the upper troposphere is particularly sensitive to oxides of nitrogen injected by aircraft.

- The temperature record indicates that a small cooling (about 0.3°C per decade, globally averaged) has occurred in the lower stratosphere over the last two decades, which is in the sense of that expected from the observed ozone change.

- Increases continue in the atmospheric abundances of source gases that affect ozone and the radiative balance. Although methane has continued to increase in the atmosphere, the rate of increase has slowed, for reasons that are not understood. Methyl bromide is the major contributor to stratospheric bromine (15 pptv). The sources of methyl bromide are not well characterized; however, significant anthropogenic emissions have been suggested.

• Recent laboratory studies have identified key heterogeneous reactions and have allowed a more-quantitative assessment of the role of global stratospheric sulfate aerosols in leading to enhanced abundances of reactive chlorine species.

• Limited observations suggest that the abundance of chlorine monoxide (ClO) in the lower stratosphere at northern middle latitudes is greater than that predicted by models containing only currently known gas-phase chemistry, and the observed seasonal and latitudinal dependences are inconsistent with those predicted. Some new studies that incorporate currently known heterogeneous processes provide an improved simulation for some observed gases, such as ClO and nitric acid.

• Present models containing only gas-phase processes cannot simulate the observed seasonal ozone depletions at middle and high latitudes. However, models incorporating currently known heterogeneous processes on sulfate aerosols predict substantially greater ozone depletion (e.g., a factor of 2 - 3 at middle latitudes) from chlorine and bromine compounds compared to models containing only gas-phase processes. Indeed, the heterogeneous models simulate most of the observed trend of column ozone in middle latitudes in summer, but only about half of that in winter.

• There is not a full accounting of the observed downward trends in global ozone. Plausible mechanisms include (i) local heterogeneous chemistry on stratospheric sulfate aerosols (as evidenced by, for example, elevated levels of ClO and the presence of sulfate aerosols at the altitudes of the observed ozone depletion) and (ii) the transport of both ozone-depleted and chemically perturbed polar air to middle latitudes (as evidenced by high levels of reactive chlorine and low levels of reactive nitrogen, which is a characteristic of chemically perturbed polar air). Although other possible mechanisms cannot be ruled out, those involving chlorine and bromine appear to be largely responsible for the ozone loss and are the only ones for which direct evidence exists.

• Since the middle latitude ozone losses are apparently due in large part to chlorine and bromine, greater ozone losses are expected as long as the atmospheric levels of these compounds continue to increase. With the increases in the levels of chlorine and bromine that are estimated for the year 2000, the additional ozone losses during the 1990s are expected to be comparable to those already observed for the 1980s.

• There are numerous ways in which further increases in stratospheric halogen abundances can be reduced. The table below illustrates the effects of reducing the emissions of several types of halocarbons. Four aspects are shown: (i) the change in peak chlorine loading, (ii) the times at which chlorine abundances have decreased back to 2 ppbv (the abundance in the late 1970s, which is when the Antarctic ozone hole started and when the accelerated trends in total-column ozone losses in the northern hemisphere began); (iii) the times at which chlorine abundances have decreased back to 3 ppbv (the abundance in the mid-late 1980s); and (iv) a measure of the cumulative ozone loss for the time period that the chlorine levels are above 3 ppbv. All of the values in the table are relative to the reference scenario (AA).

Scenarios for Reducing Chlorine Emissions

Scenario	Peak Cl (ppbv)	Year at 3 ppbv	Year at 2 ppbv	Integral (Cl>3 ppbv)
AA	**4.1 (ppbv)**	**2027**	**2060**	**22.7 ppbv-yr**
AA3	-0.18	-10 yrs	-7 yrs	-7.6
D	-0.03	0	0	-1.3
D3	-0.10	0	0	-2.9
E	0.00	-7	-3	-2.0 *
E3	-0.03 *	-10	-3	-4.4 *
F20	+0.01	0	0	+0.8
F40	+0.02	+1	0	+1.5
G20	+0.01	+5	+2	+4.2
AA3 + D3	-0.21	-11	-7	-10.4

* These values should be reduced by a factor of about 2 - 3 when evaluating ozone loss rather than chlorine loading.

Definitions of scenarios:
AA: Montreal Protocol (10 yr lag of 10% of CFCs plus CCl_4; no lag for CH_3CCl_3 and Halons). HCFC-22 increases at 3% per year from 1991 to 2020, ramps to 0 by 2040. No substitution of CFCs with HCFCs.

o Non-substitution scenarios:
AA3: 3 year acceleration of CFCs and CCl_4 schedules.
D: 3 year acceleration of CH_3CCl_3 schedule.
D3: CH_3CCl_3 on the accelerated CFC phase-out schedule.
E: HCFC-22 ramp to zero between 2000 and 2020.
E3: HCFC-22 on the accelerated CFC phase-out schedule.

o Substitution scenarios:
HCFC substitutions begin in 1995, no growth to 2000, 3% per year to 2020, ramp to zero by 2030. HCFC-A has a 2 year lifetime, one chlorine, and an ODP of 0.013. HCFC-B has a 20 year lifetime, one chlorine, and an ODP of 0.13.
F20: 20% initial substitution, HCFC-A.
F40: 40% initial substitution, HCFC-A.
G20: 20% initial substitution, HCFC-B.

- Stratospheric bromine is 30 - 120 times more efficient than stratospheric chlorine in destroying ozone on a per atom basis. Therefore, 1 pptv of stratospheric bromine is equivalent to 0.03 - 0.12 ppbv of stratospheric chlorine.

Polar Ozone

- The Antarctic ozone hole in 1991 was as deep and as extensive in area as those of 1987, 1989, and 1990. The low value of total-column ozone measured by TOMS in early October in 1991 was 110 Dobson units, which is a decrease of about 60% compared to the ozone levels prior to the late 1970s. The previously noted quasi-biennial modulation of the severity of the ozone hole did not occur during the past three years. This apparent lack of

variability in recent years may imply that halogen chemistry is becoming dominant over dynamically induced fluctuations on Antarctic ozone depletion.

• Recent laboratory studies of heterogeneous processes, reevaluated field measurements, and modeling studies have strengthened the confidence that the cause of the Antarctic ozone hole is primarily chlorine and bromine emissions.

• High concentrations of ClO have been observed in winter in the Arctic stratosphere between 16 -20 km. These observations have been incorporated into diagnostic models that have calculated localized ozone depletions of about 10% at these altitudes over a period of about a month, which are consistent with concurrent ozone measurements.

Ozone/Climate Relations

• The ozone losses observed in the lower stratosphere over the last decade are predicted to have increased the visible and ultraviolet incoming solar radiation reaching the surface/troposphere system and decreased the downward infrared radiation reaching the surface/troposphere system. For models that allow for the temperature of the stratosphere to adjust to the loss of ozone, the net effect is a decrease in radiative forcing. For middle and high latitudes throughout the year, the magnitude of this decrease may be larger than the predicted increases in the radiative forcing due to the increased abundances of CFCs over the last decade. Indeed, this ozone-induced decrease in radiative forcing could be offsetting a significant fraction of the increased forcing attributed to the increases in the abundances of all greenhouse gases over the same period. Changes in the global annual-average radiative forcing due to the observed ozone depletion are predicted to be comparable in magnitude, but opposite in sign, to those attributed to the CFCs over the last decade.

• Current tropospheric models exhibit large differences in their predictions of changes in ozone, the hydroxyl radical, and other chemically active gases due to emissions of methane, nonmethane hydrocarbons, carbon monoxide, and nitrogen oxides. This arises from uncertainties in the knowledge of background chemical composition and an inadequate understanding of chemical reactions and dynamical processes. Hence, these deficiencies limit the accuracy of predicted changes in the abundance and distribution of tropospheric ozone, which is a greenhouse gas, and in the lifetimes of a number of other greenhouse gases, including the HCFCs and HFCs, which depend upon the abundance of the hydroxyl radical.

Ozone Depletion and Global Warming Potentials (ODPs and GWPs)

• Steady-state and time-dependent ODPs have been recalculated with improved models that have incorporated more-accurate reaction rate coefficients and absorption cross sections and known heterogeneous processes on sulfate aerosols. The numerical values are generally similar to those in previous assessments.

• A new semi-empirical, observation-based method of calculating ODPs has been developed. The resulting values are generally larger (up to a factor of two as compared to some model-based estimates) for species with long stratospheric lifetimes (e.g., HCFC-22 and HCFC-142b) and slightly smaller for species with short stratospheric lifetimes (e.g., carbon tetrachloride and methyl chloroform). Since this approach utilizes more atmospheric observations and less model calculations in characterizing polar ozone losses, it is considered to be better than standard model ODPs, at least in the polar regions.

• The *direct GWPs* (with five different time horizons: 20, 50, 100, 200, and 500 years) for tropospheric, well-mixed, radiatively active species have been recalculated using updated lifetimes for methane, nitrous oxide, and the halocarbons and following the same methodology of IPCC (1990). With the exception of methane, new GWP results indicate

only modest changes from the IPCC values, but uncertainties still exist in these calculations due to limitations in knowledge of the carbon cycle.

• Because of incomplete understanding of tropospheric chemical processes, the *indirect GWP* of methane has not been quantified reliably at the time of this report, although improvements and quantifications of uncertainties in the near future are highly likely. The signs of the net changes in radiative forcing from known indirect effects have been established for some of the trace gases: methane, carbon monoxide, and nonmethane hydrocarbons, which are all positive. The sign of the changes in radiative forcing due to the nitrogen oxides cannot currently be established. Furthermore, the basic concept of a GWP may indeed prove to be inapplicable for the very short-lived, inhomogeneously mixed gases, such as the nitrogen oxides and the nonmethane hydrocarbons. Hence, the IPCC (1990) *indirect* GWPs are not only uncertain, but many are also likely to be incorrect (e.g., for the nitrogen oxides).

Related Issues

• Ultraviolet radiation. Significant increases in ultraviolet radiation have been observed over Antarctica in conjunction with periods of intense ozone depletion. Under clear-sky conditions, these increases are consistent with theoretical predictions. Furthermore, a Erythemal Radiative Amplification Factor of 1.25 ± 0.20 has been deduced from simultaneous measurements of column ozone and surface ultraviolet radiation at a clean air site, which is in agreement with a model-calculated value of 1.1. Therefore, for the first time, the response of ground-level ultraviolet radiation to changes in column ozone has been observed and quantified.

• Supersonic aircraft. A previous, independent assessment of the impact of a projected fleet of supersonic aircraft on stratospheric ozone has reported the prediction that the ozone loss increases with the amount of nitrogen oxides emitted. These models used gas-phase chemistry and assessed ozone loss for the case of 500 aircraft flying at Mach 2.4 between 17 - 20 km with an annual fuel use of 7×10^{10} kg/yr. The annual-average loss of column ozone at middle latitudes in the northern hemisphere is predicted to be 2 - 6%. For a comparable fleet operated at Mach 3.2 between 21 - 24 km, the comparable column ozone losses are 7 - 12%. However, recent evidence has shown that reactions on sulfate aerosols can change the partitioning of nitrogen oxides. Two model studies incorporating this heterogeneous chemistry have recently reexamined the Mach 2.4 case and found substantially less ozone change (-0.5% to +0.5%). These implications are being examined as part of a separate assessment.

• Shuttles and rockets. The increase in the abundance of stratospheric chlorine from one projection of U. S. annual launches of nine Space Shuttles and six Titan rockets is calculated to be less than 0.25% of the annual stratospheric chlorine source from halocarbons in the present day atmosphere (with maximum increases of 0.01 ppbv in the middle and upper stratosphere in the northern middle and high latitudes). The TOMS ozone record shows no detectable changes in column ozone immediately following each of several launches of the Space Shuttle.

• Volcanoes, ozone loss, and climate perturbations. Major volcanic eruptions, such as Mt. Pinatubo, substantially increase the stratospheric abundance of sulfate aerosols for a few years. Since laboratory and field data show that heterogeneous processes can lead to increased levels of reactive chlorine in the stratosphere, such injections have the potential to increase ozone losses temporarily. Furthermore, the increased levels of stratospheric sulfate aerosols are predicted to warm the lower stratosphere by about 4°C (which has been observed) and cool the Earth's surface by a much smaller amount.

• Tropospheric sulfate aerosols and climate. Fossil fuel emissions over the past century have increased the tropospheric sulfate aerosol concentrations. Their contribution to the

direct radiative forcing of the clear-sky northern hemisphere is opposite to that due to the greenhouse gases and is estimated to be a substantial fraction of the trace gas forcing.

Implications for Policy Formulations

The findings and conclusions of the research of the past few years have several major implications as input to policy decisions regarding human-influenced substances that lead to stratospheric ozone depletions and to changes in the radiative forcing of the climate system:

- **Continued global ozone losses:** Even if the control measures of the amended Montreal Protocol (London, 1990) were to be implemented by all nations, the current abundance of stratospheric chlorine (3.3 - 3.5 ppbv) is estimated to increase during the next several years, reaching a peak of about 4.1 ppbv around the turn of the century. With these increases, the additional middle-latitude ozone losses during the 1990s are expected to be comparable to those observed during the 1980s, and there is the possibility of incurring wide-spread losses in the Arctic. *Reducing these expected and possible ozone losses requires further limitations on the emissions of chlorine- and bromine-containing compounds.*

- **Approaches to lowering global risks:** Lowering the peak and hastening the subsequent decline of chlorine and bromine levels can be accomplished in a variety of ways, including an accelerated phase-out of controlled substances and limitations on currently uncontrolled halocarbons. Chlorine. A significant reduction in peak chlorine loading (a few tenths of a ppbv) can be achieved with accelerated phase-out schedules of CFCs, carbon tetrachloride, and methyl chloroform. Even stringent controls on HCFC-22 would not significantly reduce peak chlorine loading (at most 0.03 ppbv, especially when ODP weighted), but do hasten the decline of chlorine. Bromine. A 3-year acceleration of the phase-out schedule for the Halons would reduce peak bromine loading by about 1 pptv. If the anthropogenic sources of methyl bromide are significant and their emissions can be reduced, then *each* 10% reduction in methyl bromide would rapidly result in a decrease in stratospheric bromine of 1.5 pptv, which is equivalent to a reduction in stratospheric chlorine of 0.045 to 0.18 ppbv. This gain is comparable to that of a three-year acceleration of the scheduled phase-out of the CFCs.

- **Elimination of the Antarctic ozone hole:** The phase-out schedule of the amended Montreal Protocol, *if fully complied by all nations* and if there are no *continued* uses of HCFCs, affords the opportunity to return to stratospheric chlorine abundances of 2 ppbv sometime between the middle and the end of the next century. This is the level at which the Antarctic ozone hole appeared in the late 1970s and hence is about the level that is thought to be necessary (other conditions assumed constant, including bromine loading) to eliminate the ozone hole. *Such levels could never have been reached under the provisions of the original Protocol (Montreal, 1987).*

- **Uncertain greenhouse role of CFCs:** The weight of evidence suggests that a large part of the observed lower stratospheric decrease in ozone is the result of CFC emissions. Furthermore, the radiative impact of this ozone decrease may have largely offset the predicted direct radiative perturbations, at middle to high latitudes, due to the CFCs increases over the last decade. *Hence, even the sign of the overall radiative effect of CFC increases on the climate system over the last decade is uncertain.*

- **Utility of GWPs:** The direct GWPs are a useful indicator of the relative radiative effects of long-lived, well-mixed, radiatively active trace species. However, GWPs may be inapplicable for comparing the direct radiative effects of a long-lived, well-mixed gas to the indirect effects of a short-lived gas (for example, carbon dioxide to the nitrogen oxides). *For the latter need, the application of new tools, such as three-dimensional, fully coupled coupled chemistry-climate models may be required.*

8

Senate Commerce, Science and Transportation Committee
Hearing on
Global Change Research: **Ozone Depletion and Its Impacts**

November 15, 1991
Russell Bldg. Room 253 9:30 a.m.

Subject: **Effects of Ozone-Related Increases in UV-B Radiation on Marine Phytoplankton**

Testimony by: **C. Susan Weiler, Ph.D.**
Executive Director, American Society of Limnology and Oceanography
Department of Biology, Whitman College, Walla Walla, WA 99362

Witness' Background: I am presently the Executive Director for the American Society of Limnology and Oceanography, an organization of professional aquatic scientists which has disseminated scientific information and furthered understanding of aquatic systems since 1936. I have a B.A. in Biology from the University of California at San Diego (1972) and a Ph.D. in Oceanography from the Scripps Institution of Oceanography (1978). My research over the past 17 years has focused on the physiological ecology of marine phytoplankton. I served as a program officer for the National Science Foundation's Polar Biology and Medicine Program during 1987-88. At that time, decisions were made to establish a network of instruments for continuous monitoring UV radiation at all four U.S. Antarctic bases and in South America, and to establish a special program to study the biological consequences of stratospheric ozone depletion. I supervised the development of the UV monitoring equipment and network, and served as the program director for the special program on biological research related to ozone depletion. I have not conducted UV-B related research directly, but have remained actively involved in the UV-B research community through work as a scientific administrator, editor, meeting organizer, and workshop participant. Today I will summarize the status of UV-B research on marine phytoplankton.

INTRODUCTION

Phytoplankton are the tiny, generally free-floating and single-cell plants that form the base of the oceanic food chain. these organisms can generally grow as deep as the 1% or 0.01% light level, which reaches approximately 150 m on a sunny day in clear water. It has been known for a long time that ultraviolet radiation can penetrate to ecologically significant depths. Because of this UV-B radiation penetration, phytoplankton and other aquatic organisms are at risk from the depletion of ozone in the upper atmosphere. The depth of penetration varies with water clarity, the amount and composition of UV-B absorbing compounds, atmospheric turbidity and clouds, and with the wavelength of the UV-B radiation. Ecologically significant penetration may be more than 30 m on a sunny day in clear water. While some information exists on UV-B effects on phytoplankton, the full consequences of stratospheric ozone depletion on marine phytoplankton and ecosystems cannot yet be assessed.

UV-B affects many different processes in phytoplankton, including cell viability, DNA integrity, photosynthesis, nutrient uptake, pigmentation, motility and orientation, protein content, and cell division, and there may be positive or negative synergistic responses. At present we know little about UV-B effects on the individual systems, let alone the combined effects. These are difficult to address, particularly because effects may express themselves over different time scales.

UV-B effects on cell constituents vary tremendously with wavelength as well as intensity. The shorter the wavelength, the greater the energy and subsequent effect. Thus, it is imperative to have wavelength-specific radiation measurements when studying UV-B effects. Because absorption varies as a function of wavelength as well as depth, UV-B should be measured at each

experimental depth. And because phytoplankton cells are subject to constant vertical mixing, experiments at fixed depths can only approximate the effect on organisms experiencing natural water movement.

Visible (400 - 700 nm) and UV-A (320-400 nm) radiation and UV-B (280-320 nm) radiation are all important in the context of how organisms respond to ozone-related increases in UV-B radiation. Visible radiation is necessary for photosynthesis, which provides energy for photoprotection, photorepair and other physiological processes. While UV-A radiation is damaging, it also plays a role in photorepair processes. Because UV-A and visible radiation are not absorbed by ozone and UV-B is, the ratio of UV-B/(UV-A + Visible + UV-B) increases with decreasing ozone. Such changes in the ratio of wavelengths could alter at least some species responses. The importance of changes in this ratio for cell processes is currently under consideration.

While we do know that it is important to conduct experiments using naturally occurring spectra and ratios, research has been limited because artificial lights do not mimic the natural radiation spectrum. The recent ozone depletion over the Antarctic and the related increases in UV-B radiation have freed researchers from the constraints imposed by artificial lights. UV-B changes in the Antarctic are both large and rapid because the size, shape and position of the ozone hole varies with time. Phytoplankton and other organisms may therefore be subject over a few days to increases in UV-B comparable to past seasonal changes.

EFFECTS OF UV-B ON MARINE PHYTOPLANKTON

Effects of UV-B on marine phytoplankton include:

• **Damage to DNA and other important cellular molecules and processes**
Absorption of UV-B can cause irreparable damage to the genetic material or disrupt other metabolic processes, and can eventually result in death. Protein content, dry weight, and pigment concentration have all been found to decrease after UV-B exposure. Recent work in the Antarctic using a non-marine bacterial dosimeter found that DNA damage was directly related to atmospheric ozone concentrations; effects were found as deep as 37 m. Because a UV-B sensitive bacterial strain is needed for the dosimeter, results represent the extreme case. Researchers have demonstrated that, despite the low-light conditions characteristic of the Antarctic, phytoplankton species are similar to temperate species in their ability to produce UV-blocking compounds and repair DNA damage caused by UV radiation. However, species are variable in their capacity to resist UV-B related damage. In one study, the species varied in sensitivity by a factor of 100. More research is needed to assess species differences in protective mechanisms and to assess the response of species to different radiation conditions.

• **Reduction of phytoplankton production.**
Photosynthesis has been shown to be inhibited by UV-B radiation.
Incident UV-B doses in the Antarctic have more than doubled over pre-ozone hole values, and organisms at some locations are now getting a dose of UV-B higher even than what they would normally experience even at the summer solstice. Antarctic researchers recently found that there is a reduction of photosynthesis for populations sampled inside the ozone hole. Unpublished results indicate a 6%-12% reduction in water column primary productivity associated with a 43 % decrease in atmospheric ozone (from 350 DU outside the hole to 200 DC inside the hole). Inhibition could be related to changes in the ratio of UV-B/(UV-A + Visible + UV-B) radiation as well as the quantity of solar UV-B radiation. Because adaptation occurs on many time scales, it is not possible to accurately extrapolate from these short-term incubations at fixed depth to long-term impacts.

Although we know that photosynthesis will decline to some degree, the dose/response curve is not yet accurately known. Under natural conditions, cells do not remain at fixed depths; rather they are carried around by the mixing water. To follow cells over time, it is necessary to enclose them in bottles and incubate on shipboard or at fixed depths in the water column. The effect of this

enclosure can at best be approximated. Because of this, researchers are looking for natural indicators of UV-B status, which could be assessed without incubating samples in bottles.

Antarctic phytoplankton blooms form each spring as the marginal sea ice melts to form a lens of relatively stable water. While biomass is generally highest during late spring and early summer (Nov. - Jan.), these blooms are typically initiated in the early spring, during the ozone hole. Cells are likely to be particularly vulnerable because the stable water conditions concentrate these shade-adapted cells near the surface where UV-B levels are highest.

- **Differences in sensitivity among species**

Species vary in their sensitivity to UV-B, and even closely-related species can differ dramatically.

POSSIBLE CONSEQUENCES OF UV-B INCREASES FOR THE FOOD CHAIN

- **Changes phytoplankton species composition**

Differential sensitivity may result in changes in species composition even if total water column productivity remains unaffected. While it appears that species composition will vary in some way, it is not yet clear how it will change.

Natural variability is a problem with most global-change issues, and is particularly so when looking for ozone-related changes in natural systems. Because movement of the ozone hole results in large and rapid changes in UV-B levels which may pass over within a couple of days, adaptation over the period of ozone depletion may not be complete, and unaffected seed populations may exist in nearby areas. Cells might not be able to adapt to their full potential during one ozone-hole pass, and might revert to a pre-hole physiological state after the hole passes over. If so, the community would exist in a constant state of disequilibrium.

The ozone hole presently occurs each spring just as the sea ice is melting, and dissipates before summer. Large seasonal changes in light, nutrients and water column stability unrelated to ozone could provide large and presumably different selective pressures. For instance, spring blooms are initiated by the release of cells from melting sea ice. These low-light adapted species may not be the most resistant to springtime ozone-related increases in UV-B radiation, and they are certainly not acclimated at the time of their release even if they do have the capability to acclimate.

- **Changes in higher trophic levels**

Changes in the abundance, size distribution, or nutritional value of primary producers will affect higher trophic levels by reducing feeding efficiency and potentially causing nutritional deficiencies. Species composition might be shifted towards different size or nutritional classes, and this could reduce food availability to higher trophic levels even if total primary production remained at past levels. Thus, changes in the species composition of the primary producers could cascade through a food chain even if the higher trophic levels are not directly affected by UV damage and even if total primary production is not affected. Bottle experiments using natural populations are necessarily short term and consequently inadequate for determining long-term impacts, including changes in species composition and ecological consequences.

SUMMARY

In conclusion, recent studies confirm earlier findings and demonstrate that UV-B radiation is harmful at both pre- and post-ozone hole levels. The effect of UV-B on marine phytoplankton will increase with decreasing stratospheric ozone, and the effect of UV-B on Antarctic marine phytoplankton is likely to increase if the ozone hole gets deeper, bigger or lasts longer. We know more now than we did 10 years ago about UV-B effects on marine phytoplankton, but we do not yet know enough to accurately predict population or ecosystem responses to increases in solar UV-B radiation..

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TESTIMONY OF
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OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
BEFORE THE
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE

NOVEMBER 15, 1991

Mr. Chairman, members of the Committee, it is a pleasure to appear before you today as you consider the United States' activities regarding stratospheric ozone depletion, as well as the United Nations Environment Programme's assessments pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer. I am Dr.Robert C. Worrest, Program Manager of the U.S. Environmental Protection Agency's Stratospheric Ozone Research Program, as well as of its Global Change Research Program. Prior to my move to EPA headquarters, I was Professor of Radiation Biology at Oregon State University. My research while at Oregon State University resulted in many publications regarding the impact of enhanced levels of ultraviolet-B radiation on components of marine ecosystems. Among my publications, as co-editor, is a book entitled, "Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life." In addition, I have participated as co-author in the 1989 United Nations Environment Programme Environmental Effects Panel Report on the environmental effects of stratospheric ozone depletion, as well as for the 1991 update.

Depletion of the stratospheric ozone layer is expected to lead to an increase in the amount of UV-B radiation penetrating toward the earth's surface. Significant increases in ultraviolet radiation have been observed over Antarctica. This increased UV flux poses a potentially serious threat in several areas, including human health, agriculture, silviculture and marine ecosystems. Research indicates that increasing amounts of UV-B radiation at the earth's surface may lead to a higher incidence of skin cancer, as well as immunological alterations and cataracts in human populations.

Higher levels of ultraviolet radiation are also hypothesized to lead to crop damage and loss, and perturbations in marine ecosystems with a potential impact on fisheries.

Even with an immediate phaseout of all CFCs and related compounds, current levels of chlorine loading in the atmosphere commit the world to an unavoidable decrease in stratospheric ozone well into the next century. Ecological and human health research, as well as UV-B measurements at the ground, should be pursued in order to develop adaptive strategies to the inevitable ozone decrease before potentially serious problems arise.

The goal of EPA's Stratospheric Ozone Research Program is to provide important, new, policy-relevant information, and yield early warnings of potentially dangerous impacts from ozone depletion. To develop such policy-relevant information, the Agency's research program focuses on the impacts of ozone depletion in areas that have global implications, such as food production and human health. The Agency also examines the linkages between the problem of ozone depletion and other issues, particularly global climate change. Many of the trace gases responsible for ozone depletion are also important greenhouse gases, and other linkages exist between these two areas. The EPA research program is part of a coordinated effort including the National Aeronautics and Space Administration, the United States Department of Agriculture, the Department of Energy, the National Oceanic and Atmospheric Administration National Marine Fisheries Service, the Department of Health and Human Services National Institute of Environmental Health Sciences, and others under the auspices of the Federal Coordinating Council for Science, Engineering, and Technology Committee on Earth and Environmental Sciences.

A key challenge for EPA's research program is to target those areas of scientific uncertainty that are most useful to policy makers in addressing stratospheric ozone

depletion. This research will contribute to the success of the 1985 Vienna Convention for the Protection of the Ozone Layer and the subsequent Montreal Protocol, and to compliance with the conditions of the 1990 Clean Air Act Amendments.

For the conditions of the Protocol to be successful on a global scale, it is essential that research be focused on areas that are relevant not only to the United States and other industrialized nations, but also to developing and newly industrialized countries. In response to these mandates, EPA has developed an assessment-oriented research program on stratospheric ozone depletion conducted by the Office of Research and Development (ORD). ORD's research program is designed to play a significant role in generating scientific information that is credible to these important audiences. EPA focuses its research efforts on areas of primary importance to the mission of the Agency, building upon its own strengths and the strengths of other national and international organizations.

As decided at the first meeting of the Conference of the Parties to the Vienna Convention (Helsinki, 26-28 April 1989) in Decision 4 (UNEP/OzL.Conv.1/5), "...the following activities shall be given priority in the research, observations and transfer of technology: ...(d) Research on the human health and biological implications of ultraviolet radiation changes at the earth's surface. Particular attention must be given to the impact on food production in the developing world and to development of crop varieties resistant to higher levels of ultraviolet radiation;..."

A goal of the EPA's $6 million (FY 1992 President's request) Stratospheric Ozone Research Program is to understand the human health and biological implications of ultraviolet radiation changes at the earth's surface. Particular attention is given to the impact on food production in the developing world and to the development of crop varieties resistant to higher levels of ultraviolet radiation. Research topics covered are

(1) human health, (2) wetland rice ecosystems, (3) marine ecosystems, and (4) atmospheric and biospheric transport and fate of proposed CFC substitutes and their degradation products.

U.S. Environmental Protection Agency
Stratospheric Ozone Research Program

Human Health

UV-B radiation is suspected or known to cause significant adverse health effects, including suppression of the immune system (immunosuppression), ocular disease, and melanoma and non-melanoma skin cancer.

Summary of Research

1. Assess Immunosuppressive Effects of UV-B Radiation in Humans

The objective is to assess the nature, extent and potential clinical relevance of UV-B-induced immunosuppression in normal human subjects.

2. Assess Effects of UV-B radiation on the Development of Infectious Diseases

The objective is to determine the effects of UV-B exposure on the incidence, severity and recurrence of a spectrum of infectious diseases in experimental animals, and to evaluate the effects of UV-B radiation on host resistance and immunity.

3. Assess Effect of Elevated UV-B Exposure on the Risk of Photokeratitis

The objective is to identify geographic areas in which ambient levels of UV-B exposure will exceed the threshold for photokeratitis at progressive levels of depletion of stratospheric ozone.

4. Assess Effects of UV-B Radiation on the Effectiveness of Vaccines in Humans

The objective is to assess the effect of UV-B radiation on the establishment, effectiveness, and duration of immunization following vaccination.

Wetland Rice Ecosystems

The primary focus of research addressing the response of vegetation at EPA is to evaluate the impacts of UV-B radiation on rice, the world's most important food crop. The rice research program evaluates the effects of UV-B radiation on rice and rice cropping practices, and the effects of global climate changes that may occur simultaneously with UV-B radiation enhancement. Integrated research tasks are conducted at the International Rice Research Institute (IRRI) in the Philippines, and at EPA laboratories and academic institutions in the United States.

Summary of Research

1. Response of the Wetland Rice Ecosystem to Ultraviolet-B Radiation

The primary objective is to determine the fundamental effects of UV-B radiation on rice plants and components of the wetland rice ecosystem. Indirect effects of UV-B radiation on the wetland rice ecosystem will be measured for important rice diseases, insect pests, weeds, and nitrogen fixers.

2. UV-B Radiation and the Global Climate Change Scenarios

The main objectives are (1) to link geographic and global climate information in a Geographic Information System (GIS) environment; (2) to determine the most critical rice growing areas; and (3) to characterize current and projected future levels of UV-B radiation, CO_2, and temperature for critical rice areas.

3. Responses of the Rice Ecosystem to CO_2 Enrichment and Temperature Increases

The primary objective of this program is to determine the fundamental interactive effects of enriched CO_2 and elevated temperatures on rice plants and rice ecosystems. Of primary concern will be the effects of climate change on rice yield in the tropics, and components of rice growth and physiology. Ultimately, interaction studies will be carried out to evaluate the effects of enhanced levels UV-B radiation in the context of global climate change.

4. Effects of UV-B Radiation and Global Climate Change on Methanogenesis

The primary objective is to determine the atmospheric feedbacks between global change, including UV-B radiation, and rice methanogenesis by collecting baseline data on current methane emission rates from IRRI tropical rice paddies, and by determining the impacts of global change on methane emission rates from IRRI tropical rice fields.

5. Development, Application and Validation of Rice Response Models

The first objective is to develop, apply and validate models that describe the effects of UV-B radiation and global climate change on rice. The second objective is to link the models simulating rice ecosystem response to UV-B enhancement and global climate change with geographic and climate information stored in a GIS database.

6. Assessment of Risk to Rice Ecosystems from UV-B Radiation and Global Climate Change

The primary objective is to assess the risk to rice ecosystems from global change (including UV-B radiation, CO_2, and temperature) through use of models and GIS.

7. Assessment of Adaptive Strategies for Rice Ecosystem Responses

The primary objective is to assess adaptation strategies for the rice ecosystem in response to global changes. Principal outputs will include (1) reports assessing the impacts of UV-B radiation on wetland rice ecosystem; (2) reports assessing the impacts of global climate change on the wetland rice ecosystem; (3) recommendations regarding the use of plant breeding to adapt to potential effects of UV-B radiation and global climate change on rice; and (4) recommendations regarding the use of management practices to adapt to the effects of UV-B radiation and global climate change on rice.

Marine Ecosystems

Past efforts to understand the effects of stratospheric ozone depletion on marine ecosystems have addressed (1) the physical variables that determine the exposure (or dose) to marine ecosystems; (2) the amount of UV-B radiation that produces biological effects; (3) the direct impacts on the sensitive life stages of ecologically-important marine organisms; and (4) the extent to which the sum of the impacts might affect the marine resources significant to humans. The sum of past efforts suggests that the likelihood of significant impacts from UV-B exposure to marine environments is real even if it cannot yet be fully quantified.

Summary of Research

1. Assess the Effects of Chronic UV-B Radiation Exposure on Marine Ecosystems

The objective is to determine the effects of long-term UV-B radiation exposure on phytoplankton and zooplankton species, communities, primary and secondary production, and trace gas fluxes.

2. Examine Antarctic Ecosystems Under Current and Enhanced UV-B Conditions

The objectives are to assess the current rates of primary production and fluxes of radiatively important trace gases, and to assess the impacts on existing phytoplankton and zooplankton under current Antarctic conditions and under enhanced UV-B radiation.

3. Assess the Effects of UV-B Radiation on Fish Eggs and Larvae

The objective is to determine the direct and indirect effects of UV-B radiation on the survivorship of fish eggs and larvae. To better understand the range of sensitivity and the mechanisms of damage, UV-B radiation dose-response relationships will be determined for the eggs and larvae of several commercially and ecologically important fish species.

Atmospheric Transport and Fate of CFC Substitutes

The goal of this research program is to assess the impact of releasing large quantities of replacement compounds for ozone depleting CFCs. Major components of the life cycles of these substitute compounds must be established. The program objectives are (1) to identify (through laboratory experiments and theoretical investigations) the chemical and physical parameters controlling concentrations of CFC substitutes and their oxidation products in air and aqueous media (including oceans, rivers, and precipitation), and (2) with such data, to develop models for calculating concentrations based on emission scenarios.

Summary of Research

The approach tracks the chemical evolution of CFC substitutes by investigating their atmospheric degradation routes, their uptake to aqueous media and subsequent reactions, and finally their fate during the evaporation process.

Biospheric Fate and Transport of CFC/Halogen Substitutes

The goals of this research are to (1) define biospheric transformation pathways and products for CFC/Halogen substitutes in both homogeneous and heterogeneous systems; (2) determine appropriate rate constants for selected CFC/Halogen substitutes (and their appropriate corresponding daughter products); (3) derive algorithms to describe environmental transformations of these compounds for use in predictive models; (4) refine terrestrial and aquatic ecological risk assessment models; and (5) carry out the appropriate risk assessments.

Summary of Research

This research will enable researchers to (1) determine reaction pathways and fate constants for selected HFCs/HCFCs, their tropospheric oxidation products, and their their fate constants; (2) to determine reaction pathways and rate constants for selected terpene cleaners; and (3) to carry out ecological risk analysis on select compounds in each class of substitutes, as fate and toxicity data become available.

In addition to research carried out under the EPA Stratospheric Ozone Research Program, there is related research performed under the mandate of the 1990 Clean Air Act Amendments. What follows is a description of that research:

Engineering Plan for Stratospheric Ozone Protection

The goal of of this program is to provide scientific/engineering information on potential controls for stratospheric ozone protection (particularly pollution prevention) in support of the 1990 Clean Air Amendments, the 1990 revised Montreal Protocol, and the potential needs of accelerated phaseout schedules. The program's primary emphases will be to evaluate (in cooperation with the private sector) long-term, environmentally acceptable alternatives to ozone-depleting

substances, products made with such substances, or products containing such substances.

Summary of Research

The research areas to be addressed include the following: determining the most cost-effective ways to comply with the Montreal Protocol and Clean Air Act Amendments limiting ozone depleting compounds; complying with international treaty provisions on technology transfer and trade; increasing international participation in the Montreal Protocol; assuring that transition away from ozone depleting compounds does not create new environmental problems; development of cost-effective energy efficient substitutes; assessing the benefits and costs of developing a national recycling program; and evaluating additional potential requirements in the Protocol and Clean Air Act Amendments. However, by seeking rapid solutions, potential risks are posed to health and safety. The greenhouse issue is one important consideration because many replacements for CFCs and HCFCs are also greenhouse gases. Clean Air Act Amendments require that environmental effects such as these be addressed.

The breadth of the studies is wide. Some studies require that the specific use of a chemical be evaluated to determine its exact function and mechanics. Next, scoping plans are devised to address potential replacements (ex. Halon-1301 in total flooding fire extinguishment systems). Other studies are at the experimental stage, such as chemical replacements for aerosols). Other studies might provide assessment of a given solution for compliance with EPA regulations under the Clean Air Act Amendments. New chemicals which theoretically may be applicable must be synthesized, purified, and evaluated for their appropriate properties (i.e., compared to properties that are believed to be necessary for successful use in a given application). EPA is working with other government agencies, academia, and industry to assess, evaluate, develop, and implement

solutions as appropriate. In domestic home refrigerator/freezers, EPA is working with the Association of Home Appliance Manufacturers; individual refrigerator manufacturing companies (Amana and Whirlpool); chemical companies (Grace and Allied); research organizations (Oak Ridge National Laboratory); and universities such as Maryland, Purdue, Illinois, and Iowa State. These efforts involve modeling, component evaluation, and integrated system hardware modification and testing. In non-home refrigeration areas, a similar approach is starting, and efforts are expected to expand in 1992. In addition to domestic efforts, EPA is working with developing countries to help assess their needs and transfer technology, to assist in their efforts to reduce use of these chemicals. For example, research on home refrigerator/freezers has already involved some cooperation with India and The People's Republic of China.

EPA has already completed a project setting a standard for the recycling of refrigerants for automotive use in cooperation with the Mobile Air Conditioning Society, Motor Vehicle Manufacturers Association, Society of Automotive Engineers, and others. As a result of this effort, the Alliance for Responsible CFC Policy successfully petitioned EPA to establish a national recycling program for all refrigerants. In pursuing this approach, the Office of Research and Development works closely with the Office of Air and Radiation to develop a sensible solution.

Thank you Mr. Chairman.