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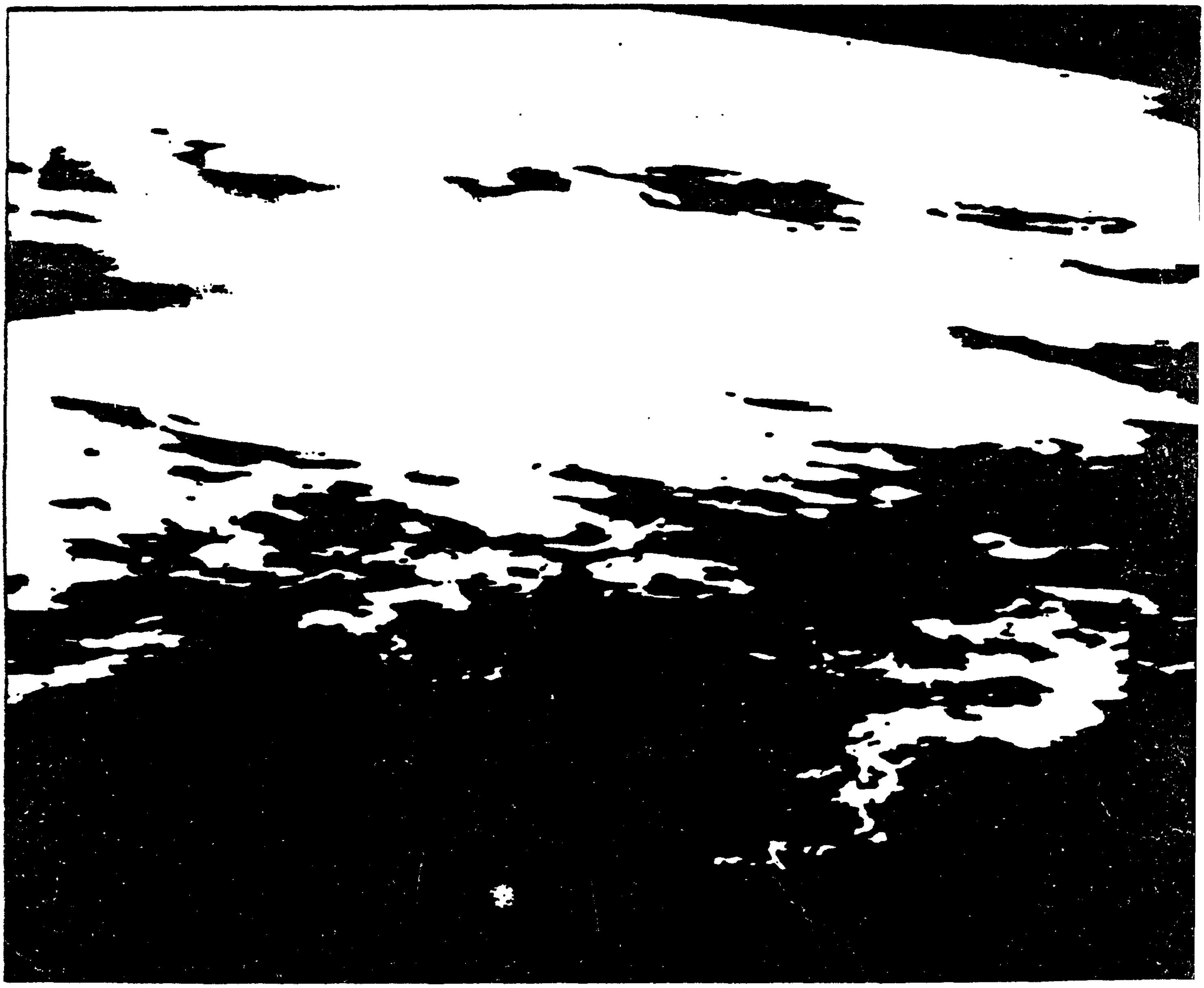
Assessing the Risks of Trace Gases That Can Modify the Stratosphere

Volume I: Executive Summary



Assessing The Risks of Trace Gases That Can Modify The Stratosphere

Volume I: Executive Summary

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Office of Air and Radiation
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Technical support documents (Volumes VI, VII, and VIII) have been published along with the first five volumes of the Risk Assessment. These documents are not part of the official Risk Assessment, and have not been reviewed by the SAB. Their publication is simply to assist readers who wish more background than available in the Risk Assessment.

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ORGANIZATION

This document summarizes a multi-volume assessment of the risks of stratospheric modification. Since the early 1970s, scientists have been concerned that human activities could alter the composition of the stratosphere, leading to reductions in the quantity of ozone protecting earth from the sun's ultraviolet-B (UVB) radiation. If such reductions in ozone levels occurred, public health and welfare would be harmed.

Substantial scientific progress has been made since concern about ozone depletion was first raised. This document represents a synopsis of current understanding of how atmospheric composition may change, the effects this change is likely to have on ozone abundance and its vertical distribution, and the impacts of these changes in ozone on skin cancer, cataracts, suppression of the immune system, polymers, plants, and aquatic systems. It also examines related changes in climate and the potential impacts of climate change on sea level rise, agriculture, human health, water resources, and forests.

Despite significant improvement in our understanding of these issues, substantial uncertainties remain. This risk assessment identifies and discusses these uncertainties and, where possible, estimates quantitatively their potential significance.

Following a brief introduction, this summary volume is organized into five sections:

- <u>Summary findings</u> (page ES-5);
- <u>Changes in atmospheric composition</u> covers chapters 2, 3, and 4 (page ES-15);
- <u>Potential changes in ozone and climate</u> covers chapters 5 and 6 (page ES-23);
- <u>Human health, welfare, and environmental effects</u> covers chapters 7 through 16 (page ES-32); and
- <u>Quantitative assessment of risks with integrated model</u> covers chapters 17 and 18 (page ES-54).

Readers desiring greater detail are encouraged to refer to the five-volume risk assessment and the three volumes of the technical support reports.

This Summary concludes with a brief listing of major prior assessments of this issue.

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INTRODUCTION

Current scientific theory and evidence indicate that continued increases in the concentrations of a variety of trace gases in the atmosphere are likely to modify the vertical distribution and column abundance of stratospheric and tropospheric ozone. Changes in the total abundance of column ozone would alter the flux of ultraviolet radiation reaching the surface of the earth, and consequently affect public health and welfare. Scientific evidence indicates that increases in ultraviolet-B radiation (UV-B) would alter skin cancer morbidity and mortality, increase cataracts, and probably suppress the human immune system. Evidence also supports the conclusion that such increases could reduce crop yields and alter terrestrial and aquatic ecosystems. Scientific theory and studies also support the conclusion that polymers would be degraded more quickly and that urban tropospheric oxidants would increase as a result of UV-B increases, although additional scientific study is needed to validate the possible effects on tropospheric air quality. The dimensions of many of these risks are at this time unquantifiable. Exhibit ES-1 summarizes these relationships.

Changes in trace gases that can modify the stratosphere can be expected to contribute to climate change in three ways: they are all greenhouse gases that would increase global warming; by modifying vertical distribution of ozone, they could change the Earth's radiative balance and climate dynamics; by adding water vapor to the stratosphere, one of these gases (methane) directly adds to the stratosphere's greenhouse or warming capacity. The effects of global warming include changes in weather and climate patterns; rises in sea level; changes in forests, hydrologic processes, and agriculture; and a variety of associated impacts.

Current science projects that changes in ozone and climate will occur slowly enough in the next decade that it is unclear that monitoring systems will be capable of clearly detecting change, or of attributing changes to particular trace gas increases. Because of the large lags expected between the emission of gases and their ultimate effect on ozone and climate, the stabilization of atmospheric concentrations and the prevention of further change would require large decreases in trace gas emissions. Consequently, while monitoring can provide a valuable system to test model projections, as well as to better understand atmospheric systems, except in the case of a larger than expected atmospheric change, monitoring cannot be expected to provide definitive information about the nature of future risks. With the exception of Antarctic ozone depletion, an unexpected and, at this time, unexplained phenomenon, past monitoring supports current models, which project that ozone depletion and climate change are likely to occur in the face of growth in the concentrations of trace gases.[1] It is important to recognize

[1] This Risk Assessment was written before the results of the two Antarctic campaigns were available and has not been revised to consider them. It now appears that the Antarctic ozone hole is at least partly caused by man-made chemicals. The implications for ozone in the rest of the world are unclear, depending on whether the loss mechanisms operating in Antarctica are likely to operate elsewhere and on whether Antarctic losses themselves might have global implications. Consequently, until those issues are resolved, we cannot conclude that the 'hole' is a portent of things to come elsewhere on the Earth. In the rest of this summary the original Risk Assessment findings on Antarctica and trends are kept intact.

EXHIBIT ES-1

The Basis for Concern About CFCs and Ozone Depletion

(1) Production of CFCs

(2) Emissions then occur

(3) Concentrations build up

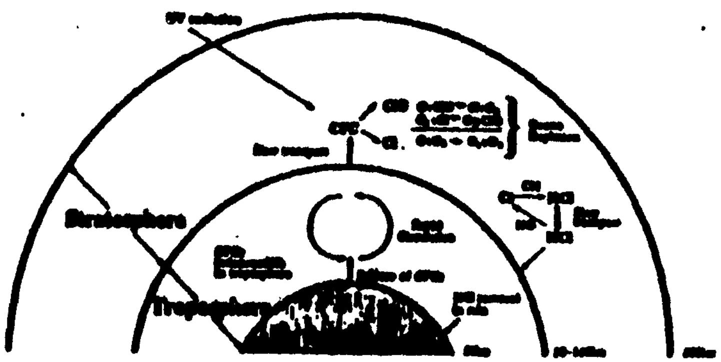
(4) Slow transport to stratosphere

(5) Photodissociation of CFCs releases chlorine

(6) Chlorine catalytically reduces ozone

(7) Ozone depletion causes changes in UV-B

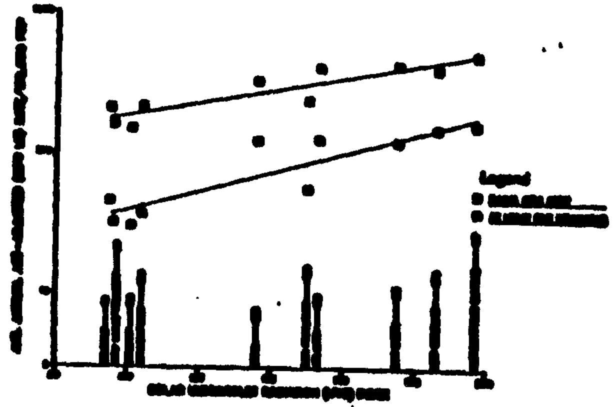
(8) CFCs and column reorganization change the climate



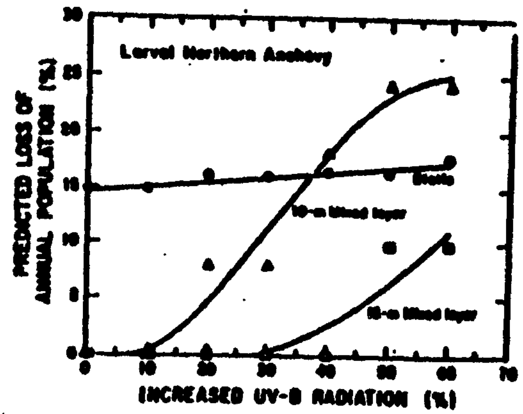
(9) Increases in UV-B produce effects

For example:

On skin cancer



On Larval Northern Anchovy



Causal Chain:

Production ——► Emissions ——► Concentrations ——► Atmospheric Response ——► UV-B and climate ——► Effects

Source: NAS (1976), Scotto (1986), and Hunter, Kaupp and Taylor (1982).

that "by the time it is possible to detect decreases in ozone concentrations with a high degree of confidence, it may be too late to institute corrective measures that would reverse this trend" (EPA Science Advisory Board, March 1987).

SUMMARY FINDINGS

Past and Possible Future Changes in Trace Gases

1. Considerable research has taken place since 1974 when the theory linking chlorine from chlorofluorocarbons (CFCs) and depletion of ozone was first developed. While uncertainties remain, the evidence to date continues to support the original theory that CFCs have the potential to decrease stratospheric ozone.

2. Atmospheric measurements show that the chemical composition of the atmosphere -- including gases that affect ozone -- has been changing. Recently measured annual rates of growth in global atmospheric concentrations of trace gases that influence ozone include: CFC-11: 5 percent; CFC-12: 5 percent; CFC-113: 10 percent; carbon tetrachloride: 1 percent; methyl chloroform: 7 percent; nitrous oxide: 0.2 percent; carbon monoxide: 1 to 2 percent; carbon dioxide: 0.5 percent; and methane: 1 percent. More limited measurements of Halon 1211 show recent annual increases of 23 percent in atmospheric concentrations.

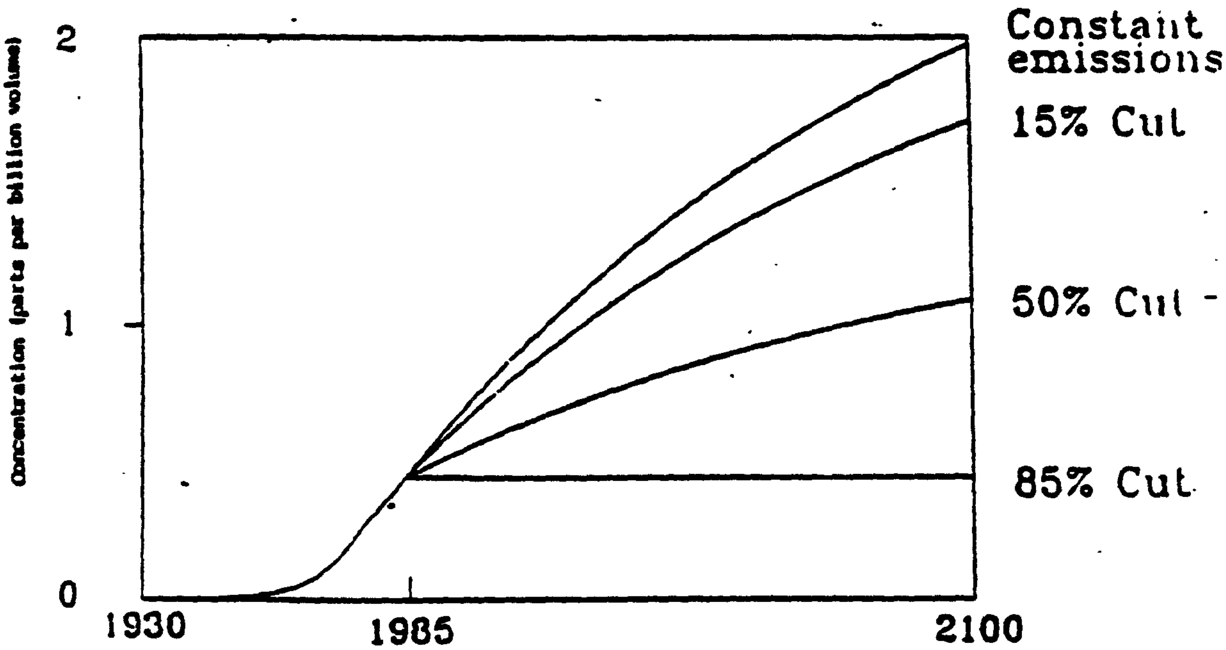
3. CFCs, Halons, methyl chloroform, and carbon tetrachloride release chlorine or bromine into the stratosphere where they act as catalysts to reduce the net amount of ozone. In contrast, carbon dioxide and methane either add to the total column of ozone or slow the rate of depletion. The effect of increases in nitrous oxide varies depending on the relative level of chlorine.

4. CFCs, methyl chloroform, carbon tetrachloride, and Halons are industrially produced. Emissions of methane, carbon dioxide, and nitrous oxide occur from both human activity and the natural biosphere. Because all these gases (with the exception of methane and methyl chloroform) remain in the atmosphere for many decades to over a century, emissions today will influence ozone levels for more than a century. Also, as a result of these long lifetimes, concentrations of these gases will rise for more than a century, even if emissions remain at constant levels. For example, to stabilize concentrations of CFC-11 or -12 would require a reduction in current global emissions of about 85 percent. (Exhibit ES-2 demonstrates effects of various reduction levels on CFC-12 concentrations).

5. In order to assess risks, scenarios of atmospheric change were evaluated using models. For CFCs, methyl chloroform, carbon tetrachloride, and Halons, demand for goods that contain or are manufactured with these chemicals (e.g., refrigerators, computers, automobile air conditioners) and the historic relationship between economic activity and the use of these chemicals were analyzed. These analyses indicate that in the absence of regulation, the use and emissions of these compounds are expected to increase in the future. However, for purposes of analyzing risks, six "what-if" scenarios were adopted that cover a greater range of future production of ozone-depleting substance than is likely to occur.

EXHIBIT ES-2

CFC-12: Atmospheric Concentrations from Different Emission Trajectories



Atmospheric concentrations of CFC-12 will continue to rise unless emissions are cut. Holding emissions constant at today's level or even 15 percent or 50 percent lower would still allow atmospheric concentrations to grow. Only a cut of 85 percent or more could stabilize atmospheric concentrations.

Source: Hoffman, 1986.

Model Projections for Ozone Changes

6. Atmospheric chemistry models were used to assess the potential effects of possible future changes in atmospheric concentrations of trace gases. Thes models attempt to simulate processes that influence the creation and destruction of ozone. While the models replicate many of the characteristics of the atmosphere accurately, they are inconsistent with measured values of other constituents, thus lowering our confidence in thei ability to predict future ozone changes accurately.

7. Based on the results from these models, the cause of future changes in ozon will be highly dependent on future emissions of trace gases. One-dimensional models project that if the use of chlorine and bromine containing substances remains constant globally, and other trace gas concentrations continue to grow, total column ozone levels would at first decrease slightly, and then would subsequently increase. If the use of CFC continues to grow at past rates and other gases also increase at recent rates, substantial total column ozone depletion would occur by the middle o the next century. If the use of CFCs stays at current levels and the growt in the concentrations of other trace gases slows over time, model results indicate total column ozone depletion will also occur. (Exhibit ES-3 shows various model projections for "what-if" scenarios.)

8. In all scenarios examined, substantial changes are expected in the vertical distribution of ozone. Ozone decreases are generally expected at higher altitudes in all scenarios in which CFC concentrations increase. Ozone increases are expected at lower altitudes in some scenarios examined due to increases in methane concentrations. Such changes may have important climatic effects.

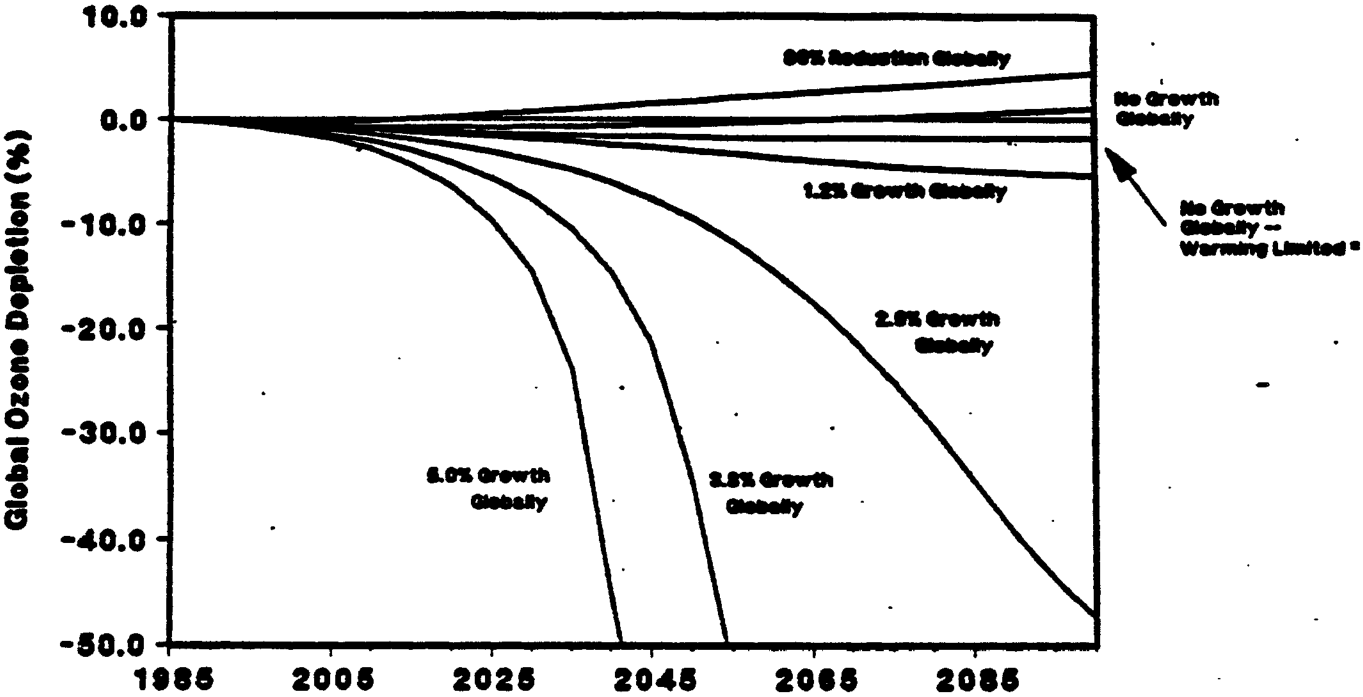
9. Two-dimensional (2-D) models provide information on possible changes in ozone by season and by latitude. Results from 2-D models suggest that global average depletion could be higher than estimates from a one-dimensional (1-D) model for the same scenario. Moreover, the 2-D model results suggest that average annual ozone depletion above the global averag would occur at higher latitudes (above 40 degrees), while depletion over tropics is predicted to be lower than the global average; and depletion would be greater in the spring than the annual average. Uncertainties in the representation of the transport of chemical species used in 2-D models introduces uncertainty in the magnitude of the latitudinal gradient of ozon depletion, but all 2-D models project a gradient.

Measurements of Ozone

10. Measurements of ozone concentrations are another valuable tool for assessin the risks of ozone modification. Based on analysis of data for over a decade from a global network of ground-based monitoring stations, ozone concentrations have decreased at mid-latitudes in the upper and lower stratosphere and increased in the troposphere. According to studies using ground-based instruments, there appears to have been no statistically significant change in column ozone between 1970 and 1983. High altitude, lower stratospheric, and total column trends are roughly consistent with current two-dimensional model predictions.

EXHIBIT ES-3

Global Average Ozone Depletion: Emission Scenarios



*This scenario assumes no growth in global production of ozone depleters, and concentrations of other trace gases are prevented from rising to an amount greater than that compatible with an increase in equilibrium global temperature of 3.0°C ± 1.5°C by 2075.

Assumptions:

-- Current 1-D models accurately reflect global depletion; Antarctic ozone hole has no impact on global ozone levels.

-- Greenhouse gases that counter depletion grow at historically-extrapolated rates.

-- Growth rates for ozone depleters are for global emissions; it is assumed that emissions do not increase after 2050.

-- Ozone depletion limited to 50 percent.

11. Recent evidence indicates that since the late 1970s substantial decreases ozone (up to 50 percent) have occurred over and near Antarctica during its springtime. These losses have been verified by different measurement techniques, and different theories have been suggested to explain the caus of the seasonal loss in ozone. Insufficient data exist to state whether chlorine and bromine are responsible for the observed depletion, or whethe some other factor is the cause (e.g., dynamics or changes in solar flux th alters NOx). Furthermore, even if man-made chemicals are the cause of the phenomenon, stratospheric conditions surrounding Antarctica are different from the stratospheric conditions for the rest of the world, so that it cannot be assumed that similar depletion would occur elsewhere. Models di not predict the Antarctic ozone depletion, however. Consequently, the change in Antarctica suggests that ozone abundance is sensitive to yet unknown natural or anthropogenic factors not yet incorporated in current models.

12. Preliminary data from Nimbus-7 suggest a decrease in global ozone concentrations (4-6 percent) may have occurred during the past several years. These data have not yet been published and require additional revi and verification. If verified, further analysis would be required to determine if chlorine is responsible for the reported decrease in ozone levels, or whether the decrease is due to other factors or reflects short-term natural variations.

Potential Health Effects from Ozone Depletion

13. Decreases in total column ozone would increase the penetration of ultraviolet-B (UV-B) radiation (i.e., 290-320 nanometers) reaching the earth's surface. (Exhibit ES-4 shows relative increases in UV-B at 295, 305, and 315 nanometers.)

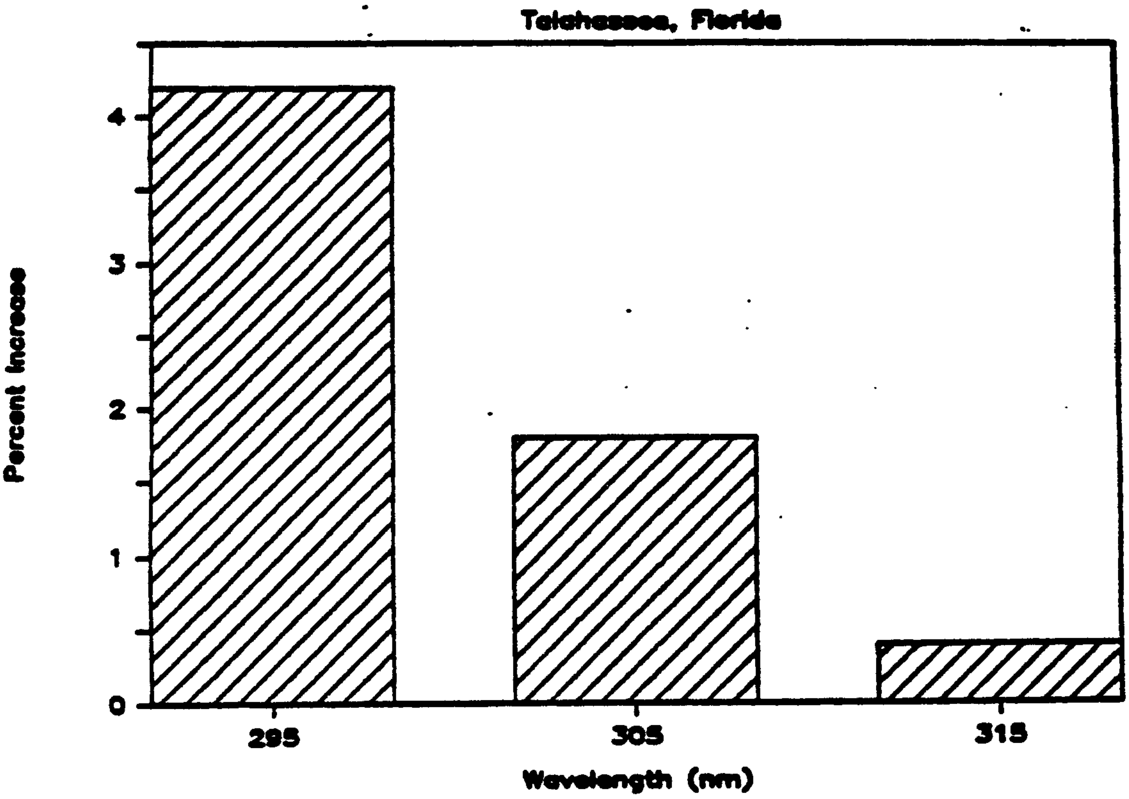
14. Exposure to UV-B radiation has been implicated by laboratory and epidemiologic studies as a cause of two common types of skin cancers (squamous cell and basal cell). It is estimated that there are more than 400,000 new cases of these skin cancers each year. While uncertainty exis concerning the appropriate action spectrum (i.e., the relative biological effectiveness of different wavelengths of ultraviolet radiation), a range relationships was developed that allows increased incidence of these skins cancers to be estimated for future ozone depletion (these cancers are also referred to as nonmelanoma skin cancers).

15. Studies predict that for every 1 percent increase in UV-B radiation (which corresponds to less than a 1 percent decrease in ozone because the amount increase in UV-B radiation, depending on the action spectrum, is greater than rather than proportional to ozone depletion), nonmelanoma skin cancer cases would increase by about 1 to 3 percent. The mortality for these forn of cancer has been estimated at approximately 1 percent of total cases bas on limited available information.

16. Malignant melanoma is a less common form of skin cancer. There are currently approximately 25,000 cases per year and 5,000 deaths. The relationship between cutaneous malignant melanoma and UV-B radiation is a complex one. Laboratory experiments have not succeeded in transforming

EXHIBIT ES-4

Increases in Ultraviolet Radiation Due to a 1 percent Ozone Depletion



Ozone depletion would lead to increases in the amount of ultraviolet radiation, particularly at the harmful lower wavelengths, that reaches the earth's surface.

Source: Estimates based on the ozone-UV model developed by Serafino and Frederick (1986).

melanocytes with UV-B radiation. However, recent epidemiological studies, including large case control studies, suggest that UV-B radiation plays an important-role in causing melanoma. Uncertainties in action spectrum, dos measurement, and other factors necessitates the use of a range of dose-response estimates. Taking into account such uncertainties, recent studies predict that for each 1 percent change in UV-B intensity, the incidence of melanoma could increase from 0.5 to 1 percent.

17. Studies have demonstrated that UV-B radiation can suppress the immune response system in animals and possibly humans. While UV-B-induced immune suppression has been linked to chronic reinfection with herpes simplex vir and leishmaniasis in animals, its possible impact on other diseases and it: impact on humans has not been studied.

18. Increases in exposure to UV-B radiation are likely to increase the inciden of cataracts and could adversely affect the retina.

Potential Effects on Plants and Aquatic Organisms

19. While studies generally show adverse impacts on plants from increased UV-B exposure, difficulties in experimental design, the limited number of speci and cultivars tested, and the complex interactions between plants and thei environments prevent firm conclusions from being made for the purpose of quantifying risks. Field studies on soybeans suggest that yield reduction: could occur in some cultivars of soybeans, while evidence from laboratory studies suggest that two out of three cultivars are sensitive to UV-B.

20. Laboratory studies with numerous other crop species also show many to be adversely affected by UV-B. Increased UV-B has been shown to alter the balance of competition between plants. While the magnitude of this change cannot be presently estimated, the implications of UV-altered, competitive balance for crops and weeds and for nonagricultural areas such as forests, grasslands, and desert may be far reaching.

21. Aquatic organisms, particularly phytoplankton, zooplankton, and the larvae of many fishes, appear to be susceptible to harm from increased exposure to UV-B radiation because they spend at least part of their time at or near surface waters. However, additional research is needed to better understa the ability of these organisms to mitigate adverse effects and any possibl implications of changes in community composition as more susceptible organisms decrease in numbers. The implications of possible effects on th aquatic food chain requires additional study.

Effects of Depletion on Tropospheric Ozone and Polymers

22. Research has only recently been initiated into the effects of UV-B on the formation of tropospheric ozone (an air pollutant with negative health and plant effects). An initial chamber and model study shows that tropospheric ozone levels could increase, resulting in additional urban areas being in non-compliance with National Ambient Air Quality Standards. The increase i UV-B would also produce ozone peaks closer to urban centers, exposing larg populations to unhealthy concentrations of tropospheric ozone. The same study also predicts substantial increase in hydrogen peroxide, an acid rai precursor. However, because only one study has been done, the results mus

be treated with caution. Additional theoretical and empirical work will be needed to verify these projections.

23. Research indicates that increased exposure to UV-B would likely cause accelerated weathering of polymers, necessitating polymer reformulation or the use of stabilizers in some products, and possibly curtailing use of certain polymers in some areas.

Climate Impacts from Trace Gas Growth

24. The National Academy of Sciences (NAS) has recommended that 1.5°C to 4.5°C represents a reasonable range of uncertainty about the temperature sensitivity of the Earth to a doubling of CO_2 or an increase in other trace gases of the equivalent radiative forcing. While some of the trace gases discussed above deplete ozone and others result in higher ozone levels, all, on net, would increase the radiative forcing of the Earth and would contribute to global warming.

25. Using the middle of the NAS range for the Earth's temperature sensitivity and a wide range of future trace gas growth (e.g., from a phase-down of CFCs by 80 percent from current levels by 2010 to a 5 percent annual increase through 2050; CO_2 doubling by 2060; N_2O increasing at 0.2 percent; CH_4 increasing by 0.017 ppm/year through 2100), equilibrium temperatures can be expected to rise from 4°C to 11.6°C by 2075. Of this amount, depending on the scenario, CFCs and changes in ozone would be responsible for approximately 15-25% of the projected climate change. (See Exhibit ES-5)

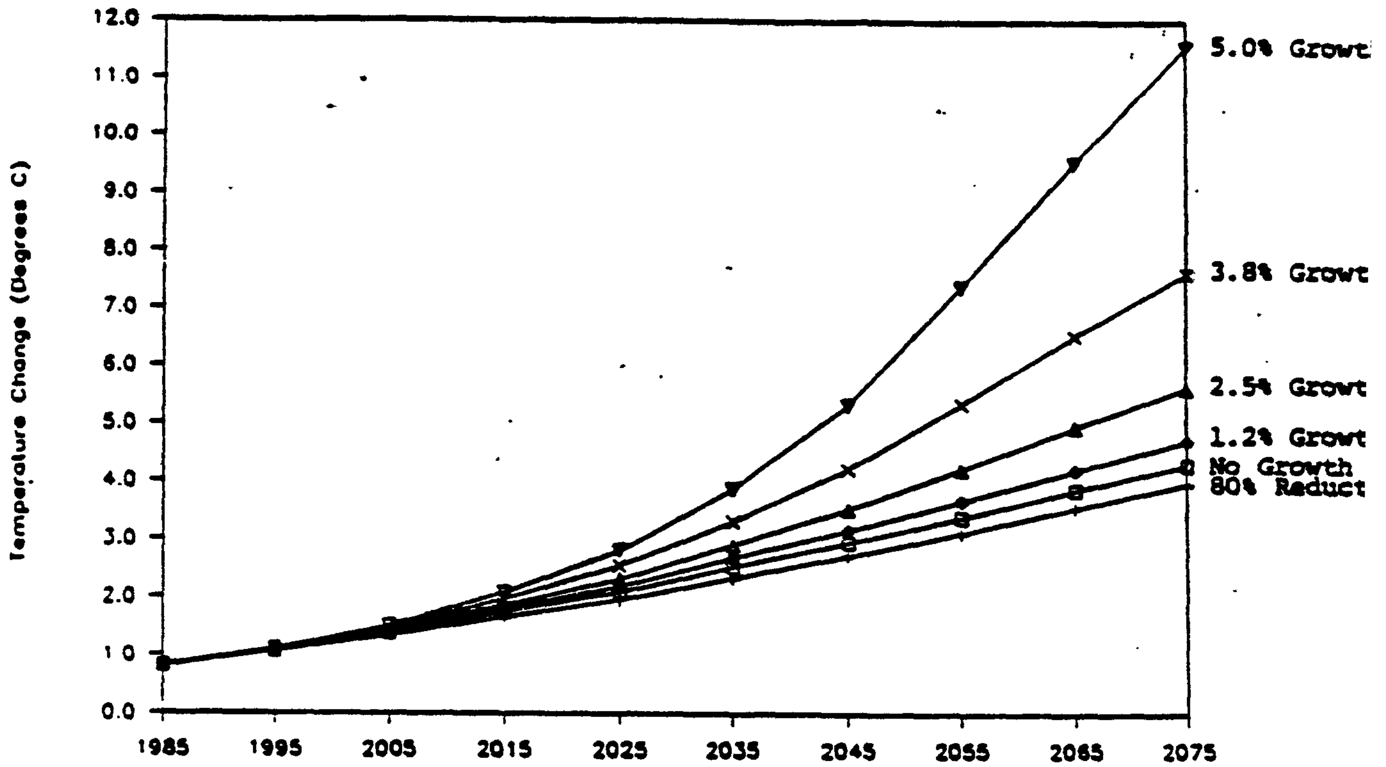
26. In most situations, inadequate information exists to quantify the risks related to climate change. Studies predict that sea level could rise by 10-20 centimeters by 2025, and by 55-190 centimeters by 2075. Such increases could damage wetlands, erode coastlines, and increase damage from storms. Changes in hydrology, along with warmer temperatures, could affect forests and agriculture. However, lack of information about the regional nature of climatic change makes quantification of risks difficult. A study suggests that rising temperatures could adversely affect human health if acclimatization lags.

Summary of Potential Risk

27. To perform the computations necessary to evaluate the risks associated with stratospheric modification, an integrating model was developed to evaluate the joint implications of scenarios or estimates for: (1) potential future use of CFCs and change in other trace gases; (2) ozone change as a consequence of trace gas emissions; (3) changes in UV-B radiation associated with ozone change; and (4) changes in skin cancer cases and cataracts associated with changes in UV-B radiation. Potential impacts of stratospheric modification that could not be quantified were not addressed by the integrating model. On a global basis, the risks of ozone depletion may be greatest for plants, aquatic systems and the immune system, even though knowledge to assess these efforts is much less certain than for skin cancers.

EXHIBIT ES-5

Equilibrium Temperature Change for the Six Emission Scenarios Assuming 3.0°C Warming for Doubled CO2*



* Computed assuming that the climate sensitivity to a doubling of carbon dioxide is 3°C. This assumption is in the middle of the NAS range of 1.5°C to 4.5°C (see Chapter 6). Note that the actual warming that may be realized will lag by several decades or more. To compute the equilibrium warming associated with high or low NAS estimates multiply the y axis 'temperature change' by 1.5 or 0.5.

Growth levels refer to global estimates of production of all ozone depleters.

28. Uncertainty about future risks is partly driven by the rate at which CFC and Halon use and other trace gases grow or decline. For this reason, a wide range of "what-if" scenarios of potential CFC and Halon use and growth in trace gas concentration was evaluated. To reflect the large uncertainties, the scenarios range from an 80 percent global phase-down in the use of CFCs by 2010 to an average annual growth in use of 5 percent per year from 1985 to 2050. For ozone-modifying gases other than CFCs, scenarios were based on recently measured trends, with uncertainties being evaluated by considering a range of future emissions and concentrations.

29. Across the wide range of "what-if" scenarios considered, ozone change by 2075 could vary from as high as over 50 percent ozone depletion to increased abundance of ozone of approximately 3 percent. This range of ozone change implies a change in the number of skin cancer cases among people alive today and born through 2075 ranging from an increase of over 200 million to a decrease on the order of 6.5 million. The overwhelming majority (over 95 percent) of the increases and decreases in skin cancer cases estimated for this wide range of scenarios is associated with basal and squamous cell cancers (i.e., nonmelanoma skin cancer). Mortality impacts are estimated to be on the order of 1.5 to 2.0 percent of the changes in total cases, and a large percentage of the estimated impacts are associated with people born in the future. The statistical uncertainty of these estimates is on the order of plus and minus 50 percent. Additional uncertainties exist, some of which cannot be quantified. The greatest single uncertainty about future risks is driven by the rate at which CFC and Halon use grows or declines. This uncertainty is reflected in the assessment by examining a wide range of "what if" scenarios of future use.

CHANGES IN ATMOSPHERIC COMPOSITION

The abundance of stratospheric ozone depends upon chemical and physical processes that create and destroy ozone. For over a decade scientists have hypothesized that changes in the concentrations of trace gases in the atmosphe could possibly perturb the processes that control ozone abundance and its distribution at different altitudes. The findings of this section summarize t currently available evidence on how emissions and concentrations of various gases may change over time. The findings in this section can be found in chapters 2 through 4 of the body of the risk assessment.

FINDINGS

1. <u>HUMAN ACTIVITIES ARE THE ONLY SOURCE OF EMISSIONS FOR THREE CLASSES OF POTENTIAL OZONE-DEPLETING CHEMICALS: CHLOROFLUOROCARBONS (CFCs); CHLOROCARBONS (CARBON TETRACHLORIDE AND METHYL CHLOROFORM); AND HALONS</u> (chapter 3)[2].

   1a. Since their development in the 1930s, CFCs have become useful chemicals in a wide range of consumer and industrial goods, including: aerosol spray cans; air conditioning; refrigeration; foam products (e.g., in cushions and insulating foams); solvents (e.g., electronics); and a variety of miscellaneous uses.

   1b. CFC-11 (CCl3F) and CFC-12 (CCl2F2) have dominated the use and emissions of CFCs, accounting for over 80 percent of current CFC production worldwide. Because of increased demand for its use as a solvent, CFC-113 (CCl2FCClF2) has become increasingly important as a potential ozone-depleting chemical.

2. <u>MEASUREMENTS OF TROPOSPHERIC CONCENTRATIONS OF INDUSTRIALLY PRODUCED POTENTIAL OZONE-DEPLETING GASES SHOW SUBSTANTIAL INCREASES</u> (chapter 2).

   2a. Measurements of current global average concentrations of CFC-11 are 200 parts per trillion volume (pptv), CFC-12 are 320 pptv, CFC-113 are 32 pptv, carbon tetrachloride (CCl4) are 140 pptv, and methyl chloroform (CH3CCL3) are 120 pptv.

   2b. Based on measurements from a global monitoring network, worldwide concentrations of chlorine-bearing perturbants (i.e., potential ozone depleters) have been growing annually in recent years at the following rates: CFC-11 and CFC-12 at 5 percent; CFC-22 (CHClF2) at 11 percent; CFC-113 at 10 percent; carbon tetrachloride (CCl4) at 1 percent; and methyl chloroform at 7 percent.

   2c. Limited measurements show that global tropospheric concentrations of Halon 1211, a bromochlorofluorocarbon containing both chlorine and bromine (which is potentially more effective at depleting ozone), have been growing recently at 23 percent annually. Concentrations have been measured as one pptv.

   2d. Measurements of tropospheric concentrations of Halon 1301, another brominated compound that is a potential ozone depleter, estimate that concentrations are approximately one pptv. No trend estimates have been published.

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2 The chapter references refer to the main body of the risk assessment.

3. ALMOST ALL EMISSIONS OF CFC-11, -12, -113, HALON 1211, AND HALON 1301 PERSIST IN THE TROPOSPHERE WITHOUT CHEMICAL TRANSFORMATION OR PHYSICAL DEPOSITION. AS A RESULT, MOST OF THESE EMISSIONS WILL EVENTUALLY BE TRANSPORTED TO THE STRATOSPHERE (chapter 2).

3a. Gases which are photochemically inert accumulate in the lower atmosphere. Their emissions migrate to the stratosphere slowly. Estimates of their atmospheric lifetimes (generally calculated base on the time when 37 percent of the compound still remains in the atmosphere) are the following: CFC-11 is 75 years (107/58 years); CFC-12 is 111 years (400/55 years); CFC-113 is 90 years; CCl4 is 50 years; Halon 1211 is 25 years; N20 is 150 years; and Halon 1301 is 110 years. (Where provided, the range in parentheses shows one standard deviation).

3b. Because of their long atmospheric lifetimes, the concentrations of these gases are currently far from steady state and will increase over time unless there is a large reduction in future emissions.

3c. Because of their long atmospheric lifetimes, these gases would continue to contribute to possible future ozone depletion and clima change (CFCs and other gases affecting ozone are also greenhouse gases) long after they are emitted. Full recovery from any depleti or climate change would take decades to centuries.

4. WHILE CFCs USED IN AEROSOLS DECLINED FROM 1974 UNTIL 1984, NONAEROSOL USE OF CFCs HAVE GROWN CONTINUOUSLY AND APPEAR CLOSELY COUPLED TO ECONOMIC GROWTH (chapter 3).

4a. From 1960 to 1974, the combined production of CFC-11 and CFC-12 fro both aerosol and nonaerosol applications grew at an average annual rate of approximately 8.7 percent. Total global CFC-11 and -12 production peaked in 1974 at over 700 million kilograms.

4b. From 1976 to 1984, sales of CFC-11 and CFC-12 for aerosol applications declined from 432 million kilograms to 219 million kilograms, an average annual rate of decline of over 8 percent. During the same period, sales for nonaerosol applications grew from 318 million kilograms to 476 million kilograms, an average annual compounded growth rate of 5 percent. By 1986, total CFC-11 and -12 global production was nearly that in 1974.

5. STUDIES OF FUTURE PRODUCTION OF CFCs-11 AND -12 PROJECT AN AVERAGE ANNUAL GROWTH RATE OF APPROXIMATELY 1.0 TO 4.0 PERCENT OVER THE NEXT 15 TO 65 YEARS (chapter 3).

5a. A large number of studies of future global demand for CFCs were conducted by experts from six countries under the auspices of the United Nations Environment Programme. These studies used a variety of methods for estimating both near- and long-term periods. In general, these studies assumed that: (1) demand for CFCs was drive by economic factors; (2) no additional regulations on CFC use were imposed; and (3) consumers or producers do not voluntarily shift aw from CFCs because of concern about ozone depletion. These studies provide a range of growth rates for developing alternative baseline scenarios of future CFC use and emissions.

5b. In general, these studies projected that CFC aerosol propellant applications would remain constant or decrease further in many regions of the world.

5c. In the U.S. over the past four decades new uses of CFCs have developed first in refrigeration, then in aerosols, then in foam blowing, and then in solvents.

5d. Studies have projected that growth in developed countries for nonaerosol applications is expected to be driven by increased use in foam blowing (primarily for insulation) and as solvents, and by the continued introduction of new uses. The wide range of estimates of future growth reflects the large uncertainties related to population and economic growth, and technological change.

5e. Studies suggest that future CFC use in developing countries will grow faster (i.e., at a higher rate) than future CFC use in the developed world. Nevertheless, the projected rates for the developing countries are lower than the historical rates that have been experienced in wealthier countries. While these studies were done using aggregate relationships of GNP and CFC use, they made different assumptions about how closely the pattern of CFC use in developing nations would replicate the pattern in developed nations, generally assuming lower use rates. However, evidence from one recently completed study (not completed at the time of the UNEP workshop) indicates that in developing countries the penetration of CFC-using goods may be occurring faster than expected on the basis of the historical relationship in developed nations. If that study is correct, growth in developing nations would be larger than projected in the above-mentioned studies, which generally assumed less penetration in developing nations than had occurred in developed nations.

5f. Three long-term studies of CFC demand report annual average rates of growth for CFC-11 and CFC-12 over the next 65 years ranging from 0.2 percent to 4.7 percent, with a median estimate of about 2.5 percent. The "what-if" scenarios used for quantitative risk assessment in Chapter 18 span a wider range of growth, including one scenario with substantial decline.

5g. Limited studies on CFC-113 and CFC-22 project that in the absence of regulation or voluntary shifts away from these chemicals, their growth will increase at a faster rate than CFC-11 and -12 as new markets develop and existing ones expand (e.g., use of CFC-113 as a solvent in metal cleaning).

6. THE CHLOROCARBONS (METHYL CHLOROFORM AND CARBON TETRACHLORIDE) ARE USED PRIMARILY AS SOLVENTS AND CHEMICAL INTERMEDIATES. ANALYSIS SUGGESTS LIMITED FUTURE GROWTH FOR THESE CHEMICALS (chapter 3).

6a. Methyl chloroform is primarily used as a general purpose solvent. Global use in 1980 was estimated at nearly 460 million kilograms. Limited analysis of future demand indicates that it is expected to grow at the rate of growth of economic activity (as measured by GNI Factors affecting future demand include possible control on it or other solvents due to their health effects. Thus, use of methyl chloroform could increase if other solvents are found more dangerou Similarly, its use could be increased if CFC-113 use is restricted. Because methyl chloroform has a substantially shorter atmospheric lifetime than CFC-113, it has relatively less potential for depleti ozone.

6b. Carbon tetrachloride is primarily used to make CFCs in the U.S. Ir developing countries it is also sometimes used as a general purpose solvent. In general, future production and emission of carbon tetrachloride is expected to follow the pattern of production of CFCs.

7. HALONS, ON A PER POUND BASIS, POSE A GREATER THREAT (2-1/2 TO 12-1/2 TIME TO OZONE DEPLETION THAN DO CFCs (chapter 3).

7a. Halons have been used in hand-held and total-flooding fire extinguishers since the 1970s. Annual production has been limited (approximately 20,000 kilograms) and emissions have been assumed to be only a small fraction of production based on the assumption that the halons remain inside the fire extinguishers. Recent research suggests the proportion of Halons released may be substantially higher. In the U.S., industrial response to concern about depletio from halons is likely to lead to some voluntary steps to curtail emissions.

7b. A single study has projected future demand for Halons.[3] It indicat that near-term demand is growing rapidly and that production may double by the year 2000. In that study, longer-term demand is judg uncertain and may range from an average annual decline of 1 percent from 2000 to 2050 to an annual increase exceeding 5 percent.

7c. The expected rate of Halon emissions is very uncertain. The one study assumed most production would remain within fire extinguisher systems as part of a growing Halon "bank." That study has been the basis for scenarios used in this analysis.

7d. The historic growth in Halon 1211 concentrations (recently measured at over 20% per year) is significantly higher than the rate assumed for future years in the one existing study.

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[3] Since the Risk Assessment was drafted, another study has been developed see Chapter 3 Appendix. That study was not included in this Risk Assessment.

7e. Discussions with Halon users indicate that Halon 1301 emissions may be underestimated in the study used for this risk assessment. A recent survey showed that existing systems are undergoing widespread testing and accidental discharge occurs more frequently than assumed in prior studies.[4]

7f. Additional analysis of Halon emission estimates are necessary to assess more adequately the risks associated with this trace gas.

8. FUTURE CONCENTRATIONS OF STRATOSPHERIC PERTURBANTS THAT HAVE AT LEAST SOME BIOGENIC SOURCES, CARBON DIOXIDE, METHANE, AND NITROUS OXIDE, ARE DIFFICULT TO PROJECT (chapter 4).

8a. The size of existing source terms (wetland areas, for example) is not known with certainty today for all these trace species. Greatest uncertainty exists for methane, least for CO2. To estimate future emissions reliably requires estimating the growth of source terms (e.g., acreage of rice paddies, wetlands area), which will be determined by many technical, political, environmental, and social factors.

8b. Current emission factors for each source term must be estimated; some are not known today or have not been reliably estimated (emissions from soils, for example).

8c. Possible changes in emission factors due to changes in the environment must be projected. Projection of changes is difficult because the underlying physical or biological processes that determine emissions are not well understood and because changes in the environment that could alter emissions are not easy to project.

8d. Biogeochemical cycles that control the fate of emissions once released into the atmosphere must be understood to determine future concentrations of these trace species; severe limitations to our current understanding of these cycles limits our capacity to determine the consequences of changing emissions in the future.

8e. Possible changes in these biogeochemical cycles due to changes in the environment must be projected; again deficiencies in existing knowledge makes this task difficult.

9. DESPITE THE UNCERTAINTIES ASSOCIATED WITH EACH OF THESE FACTORS, RESEARCHERS HAVE DEVELOPED SCENARIOS FOR THREE GASES WHICH ARE COMMONLY USED. IN THIS RISK ASSESSMENT A SCENARIO CONSISTENT WITH ONES USED IN THE ATMOSPHERIC COMMUNITY'S WILL BE ADOPTED, AS WELL AS SEVERAL SENSITIVITY SCENARIOS TO EXAMINE THE SENSITIVITY OF ATMOSPHERIC EVOLUTION TO THE SCENARIOS (chapter 4).

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[4] Since this risk assessment was originally completed, Halon users in the U.S. have taken a variety of steps to reduce emissions. This step is not considered in this Risk Assessment.

9a. The scenarios used in this risk assessment are consistent with that commonly used by the atmospheric community and assume the following changes in trace gas concentrations:

- for CO_2, a scenario developed by the National Academy of Sciences (its 50th percentile, i.e., pre-industrial CO_2 concentrations doubling by about 2065);
- for CH_4, a linear increase in concentrations of 0.017 ppm per year;
- for N_2O, concentration increases of 0.2 percent per year.

9b. Additional scenarios used to analyze risks will include:

- for CO_2

  - NAS 25th percentile (pre-industrial concentrations doubling by 2100)
  - NAS 75th percentile (pre-industrial concentrations doubling by 2050)

- for CH_4

  - 0.01275 ppm per year growth in concentrations (75 percent of the historically observed 0.017 ppm per year increase)
  - 0.02125 ppm per year growth in concentrations (125 percent of the historically observed 0.017 ppm per year increase)
  - 1 percent compound growth per year in concentrations
  - 1 percent compound growth per year in concentrations from 1985 to 2010, followed by constant concentrations at 2.23 ppm
  - 1 percent compound growth per year in concentrations from 1985 to 2020, growing to 1.5 percent compound annual growth by 2050 and thereafter

- for N_2O

  - 0.15 percent per year compound growth in concentrations
  - 0.25 percent per year compound growth in concentrations

10. <u>DECISION MAKERS SHOULD BE MADE AWARE THAT THE MOST COMMONLY USED SCENARIOS IN STRATOSPHERIC MODELING IMPLICITLY ASSUME THAT FUTURE DECISION MAKERS NEVER TAKE ACTION TO LIMIT THE RISE IN CONCENTRATIONS OF CARBON DIOXIDE, METHANE, AND NITROUS OXIDE, THREE GASES CONTRIBUTING TO THE GREENHOUSE WARMING</u> (chapter 4).

10a. **The standard assumption in most atmospheric modeling has been, by default, that greenhouse gases will be allowed to increase without limit regardless of the level of global warming that occurs or is projected.**

10b. **In order to provide decision makers with adequate information to assess the risks of ozone modification due to rising CFCs and Halons, alternative assumptions about the future of greenhouse gases need to be examined. Two scenarios are examined:**

- **limiting global warming to 2°C.**
- **limiting global warming to 3°C.**

POTENTIAL CHANGES IN OZONE AND CLIMATE

MODELS OF THE ATMOSPHERE THAT INCORPORATE CURRENT SCIENTIFIC UNDERSTANDING OF CHEMISTRY AND PHYSICS PROJECT CHANGES IN GLOBAL OZONE (TOTAL COLUMN AND/OR VERTICAL DISTRIBUTION) AND INCREASES IN GLOBAL SURFACE TEMPERATURE IF TRACE GAS CONCENTRATIONS GROW SIGNIFICANTLY. UNCERTAINTIES ABOUT MAGNITUDES REMAIN LARGE.

Models that incorporate current scientific understanding are used as the primary tool to project the potential consequences of future changes in abundances of trace gases. These models can be partly tested by comparing their results with measurements of the atmospheric, historically observed changes in ozone, and in the case of climate, with paleoclimatic and extraterrestrial environments. While current models accurately represent some aspects of the atmosphere, they fail to replicate other characteristics. This section summarizes the currently available evidence on how changing atmospheric abundance could modify total column ozone, alter column distribution, and change global climate.

FINDINGS

11. STRATOSPHERIC MODELING PROJECTS THAT THE COMBINED EFFECTS OF A VARIETY OF TRACE GASES (CHLOROFLUOROCARBONS, NITROUS OXIDE, CARBON DIOXIDE, HALONS, AND METHANE) ARE LIKELY TO REDUCE THE COLUMN DENSITY OF OZONE UNLESS EMISSIONS OF OZONE DEPLETERS ARE PREVENTED FROM GROWING (chapter 5).

11a. Photochemical theory continues to support the conclusion that chlorine, nitrogen, and hydrogen can catalytically destroy ozone in the stratosphere, thus depleting column levels.

11b. One-dimensional (1-D) models currently predict a 5-9 percent depletion for the equilibrium concentrations of chlorine that would result from constant emission of CFCs at 1977 levels. While useful for intercomparing models, these values cannot be used to assess the risks of depletion in an atmosphere in which other gases are also changing.

11c. One-dimensional (1-D) models predict average column ozone will decrease if global emissions of CFCs and other ozone depleters continue to rise from current levels, even if concentrations of methane, carbon dioxide, and nitrous oxide continue to grow at past rates. For a 3 percent growth of CFCs, models predict over a 25 percent depletion by 2075 if the other gases continue to grow.

11d. Two-dimensional models (2-D) used in steady state multi-perturbant studies that include chlorine, methane, and nitrous oxide project depletion higher than global averages at latitudes greater than 40°N, especially in the spring.

11e. Time-dependent simulations of stratospheric change in which 2-D models are used predict that depletion over 4 percent will occur at some latitudes for all cases of positive growth in CFC emissions. Such models even predict ozone depletion of up to 3 percent at inhabited latitudes for a scenario in which emissions of chlorine-bearing substances are reduced from current to 1980 levels and in which halon emissions are eliminated, but in which the greenhouse gases that counter depletion are allowed to grow at historical rates.

11f. Time-dependent simulation with one 2-D model, with CFCs growing at 3 percent, methane rising at 1 percent, nitrous oxide at 0.25 percent and carbon dioxide growing at 0.6 percent, projects annual average depletion at 40°N of approximately 1.1 percent by 2000 and 5.2 percent by 2030. At 50°N, depletion is projected to be 1.5 percent by 2000 and 6.5 percent by 2030. At 60°N, depletion is projected to be 2.1 percent by 2000 and 8.1 percent by 2030. Springtime depletion would be higher.

11g. Time-dependent simulation with one 2-D model, with CFC-11 and -12 emissions rolled back to 1980 levels, CFC-113 capped, other chlorinated emissions and bromine emissions eliminated, methane rising at 1 percent, nitrous oxide at 0.25 percent, and carbon dioxide at 0.6 percent, projects depletion by 2030 of about 0.5 percent at 40°N, 0.7 percent at 50°N, and 1.1 percent at 60°N (these depletion values are from 1985 levels). If carbon dioxide concentrations are prevented from growing from current levels, depletion would be anticipated to be higher.

11h. Time-dependent simulations with two other two-dimensional models sho roughly comparable results to those reported here, with a slightly less latitudinal gradient. However, these models also project latitudinal gradients from equatorial to polar and regions.

11i. Because of possible increases in the emissions of bromine molecules (see Chapter 4), Halons present a more important risk for stratospheric depletion than has generally been appreciated.

12. CURRENT THEORY AND MODELS FAIL TO REPRESENT ALL OBSERVATIONAL MEASUREMENTS OF THE ATMOSPHERE AND PROCESSES THAT WILL INFLUENCE STRATOSPHERIC CHANGE I A COMPLETE AND ACCURATE MANNER (chapter 5).

12a. While accurately reproducing many measurements in the current atmosphere, current models fail to reproduce some measurements; the amount of ozone at 40 kilometers is underestimated, for example.

12b. While including representations of most atmospheric processes, current models fail to include all the processes that influence stratospheric composition and structure in a realistic manner. Transport processes, for example, are represented in a simplified manner that does not encompass all the complications of movement in the real atmosphere.

12c. The inability of models to wholly reproduce measurements of the current atmosphere lowers our confidence in them to predict the future; it is possible that models are over- or under-predicting future depletion.

13. UNCERTAINTY ANALYSES THAT CONSIDER A RANGE OF POSSIBLE VALUES FOR CHEMICAL AND PHYSICAL INPUTS CRITICAL FOR MODEL ESTIMATION OF DEPLETION INDICATE THAT DEPLETION IS LIKELY IF CFCs CONTINUE TO GROW (chapter 5).

13a. Uncertainty analyses conducted with one-dimensional models predict depletion for a variety of CFC levels.

13b. Uncertainty analyses using different sets of kinetics and cross sections have not been tested in two-dimensional models. However, different 2-D models have used different approaches for transporting species. This provides a useful test of the sensitivity of model predictions to the uncertainty of how transport actually works. While differing somewhat in the latitudinal gradients of depletion, the models with different transport both predict depletion that increases with distance from the equator.

13c. Not all uncertainties can be tested in the modeling process. The possibility that missing factors may lead to a greater or lesser depletion than indicated in formal uncertainty analyses cannot be excluded.

14. OZONE MONITORING SHOWS CHANGES IN OZONE ROUGHLY CONSISTENT WITH MODEL PREDICTIONS, WITH TWO EXCEPTIONS (chapter 5).

14a. Measurements by balloons and Umkehr show 3 percent depletion at mid-latitudes in the upper atmosphere, 1.3 percent depletion in the lower stratosphere, and 12 percent increases in the lower troposphere. Uncertainty exists about the accuracy of all these observations. These results, however, are roughly consistent with the expectations generated by one-dimensional and two-dimensional models. The ground based measurement system covers only a small part of the Earth and is limited at high latitudes.

14b. Nimbus 7 measurements appear to show a decrease in global ozone, especially at both poles. However, the decrease in Arctic ozone from 1978 to 1984 may have occurred only in the last several years. Concern exists about calibration problems, which make an exact determination of the absolute magnitude of depletion difficult. However, the latitudinal variations in depletion seem to indicate that a real phenomenon is being observed, not just instrumental drift.

14c. The cause of these apparent ozone decreases measured by Nimbus 7 has not been sufficiently analyzed to determine whether the changes (if they are real) can be attributed to manmade chemicals. Other possible explanations include natural variations caused by solar cycles or other processes. The latitudinal gradients of the changes, are, however, roughly consistent with those projected by 2-D model results, although the magnitude is substantially larger than models predict. Until further analysis is performed to determine whether depletion is actually occurring and whether it can be attributed to man-made chemicals, models to assess risks to the stratosphere should not be revised.

14d. Measurements in the Antarctic spring show that the gradual depletion that occurred in the mid-1970s over and near Antarctica has given way to a steep non-linear depletion from 1979 to 1985. The ozone maximum outside Antarctica (between 50°S and 70°S) appears to be showing a decline. The depletion of all areas south of 80°S appears to be 16 percent.

14e. Models with conventional chemistry do not predict "the Antarctic ozone hole." Care should be exercised in interpreting the meaning of the phenomenon. Several hypotheses have been put forward, including a chemical explanation that attributes the loss of ozone to manmade sources (bromine and chlorine), a chemical explanation that attributes the loss to natural sources (NOx, solar cycle), or an explanation that claims the phenomenon is entirely due to the change in climate dynamics. Until more is understood about the true causes of the hole, it is impossible to determine whether the hole is a precursor of atmospheric behavior that will occur in other regions of the world. Until a better understanding of the mechanisms creating the depletion is obtained, the existence of the Antarctic ozone hole should not be used as a basis for making regulatory decisions.

14f. This risk assessment will assume that Antarctic ozone and global trends have no implications for global projections. Future reviews should update this conclusion as necessary.

15. INCREASES IN THE ABUNDANCE OF CFCs AND OTHER TRACE GASES CAN INCREASE GLOBAL TROPOSPHERIC SURFACE TEMPERATURES. THESE GASES CAN ALTER THE VERTICAL DISTRIBUTION OF OZONE AND INCREASE STRATOSPHERIC WATER VAPOR, THEREBY INFLUENCING GLOBAL WARMING (chapter 6).

15a. Trace gases that act as stratospheric perturbants also are greenhouse gases--as their concentrations increase in the troposphere they will retard the escape of infrared radiation from earth, causing global warming.

15b. Increases in methane (CH4) will also add water vapor to the stratosphere, thereby enhancing global warming. Methane increases will also add ozone to the troposphere, where it acts as a strong greenhouse gas that will further increase global warming.

15c. In all model-generated scenarios of ozone depletion, ozone decreases in the stratosphere above 28 km. This allows more ultraviolet radiation to penetrate to lower altitudes where the "self-healing effect" increases ozone to partially compensate for the ozone loss above. In some scenarios sufficient depletion occurs so that ozone eventually decreases at all altitudes.

15d. Decreases in ozone at approximately 28 km or above will have a warming effect on the Earth. There is a small net gain in energy because the increase in ultraviolet radiation (UV-B) allowed to reach the earth's surface more than compensates for the infrared radiation that is allowed to escape due to depletion of ozone above that altitude.

15e. Below approximately 28 km, increases in ozone are more effective as absorbers of infrared radiation. Consequently, increases in ozone below 28 km also will produce a net warming. In this case, the additional UV blocked by more ozone is less than the additional infrared that is blocked from escaping the earth. Conversely, a decrease in ozone below 28 km will tend to cool the Earth's surface.

15f. The direct effect of column depletion of ozone on global temperatures will depend on the magnitude of the depletion. Until the depletion is of sufficient magnitude that it occurs at the lower part of the column, ozone depletion will be a net contributor to global warming. If the stratosphere continues to deplete so that ozone is depleted below 28 km, this depletion will cause a cooling. One-dimensional models differ from two-dimensional models in the vertical distribution of ozone change, with depletion occurring at all altitudes in the higher latitudes in two-dimensional models, rather than just at high altitudes. Thus, according to 2-D models, the changes in radiative balance will be latitude dependent. At the current time, no studies have been undertaken to determine the net radiative forcing of changes projected by 2-D models.

15g. Radiative forcing may vary strongly with changes in ozone at different altitudes and latitudes. Consequently, until comparisons are made between the models in terms of their global impact, estimates of the effects of changes in the vertical column of ozone on global warming made with 1-D models must be viewed cautiously. In addition, changed vertical distribution of ozone could influence stratospheric dynamics.

16. INCREASES IN TRACE GAS CONCENTRATIONS ASSOCIATED WITH STRATOSPHERIC MODIFICATION ARE LIKELY TO WARM THE EARTH SIGNIFICANTLY (chapter 6).

16a. Two National Academy of Sciences panels have concluded that the equilibrium warming for doubling atmospheric concentrations of CO_2, or for an equivalent increase in the radiative forcing of other trace gases, will most likely be between 1.5° and 4.5°C.

16b. The magnitude of warming that would be directly associated with radiative forcing from increases in trace gases without feedback enhancement would increase temperature by approximately 1.2°C for a doubling of CO_2, and approximately an additional 0.45°C for a simultaneous doubling of N_2O and CH_4. Direct radiative forcing from a uniform 1 ppb increase in both CFC-11 and CFC-12 would increase temperature by about 0.15°C.

16c. The initial warming from direct radiative forcing would change some of the geophysical factors that determine the earth's radiative balance (i.e., feedbacks will occur) and these changes would amplify the initial warming. Increased water vapor and altered albedo effects (snow and ice melting, reducing the reflection of radiation back to space) have been projected by several modeling groups to increase the warming by as much as 2.5°C for doubled CO_2 or its radiative equivalent. Large uncertainties exist about the feedbacks between global warming and clouds, which could further amplify, or possibly reduce, the magnitude of warming.

16d. The three major general circulation modeling groups in the U.S. estimate an average global warming of around 4°C for doubled CO_2 or its radiative equivalent. However, because of uncertainties in the representation of the cloud contributions, greater or lesser amplifications, including a negative feedback that would reduce the warming to 2°C or an even lower value, cannot be ruled out.

16e. Global average temperature has been estimated as having risen about 0.6°C over the last century. This increase is consistent with general predictions of climate models. Attempts to use these data to derive empirically the temperature sensitivity of the earth to a greenhouse forcing are not likely to succeed. Uncertainty about the past concentrations of trace gases in the atmosphere, other exogenous factors that affect the climate (such as aerosols or solar input), and oscillation and instabilities in the internal dynamics of the climate system (such as ocean circulation), currently prevent the derivation of the earth's temperature sensitivity from examination of the historic rise of temperature. This limitation is likely to remain for more than another decade.

16f. The global warming associated with increases in ozone-modifying gases varies with scenarios of future growth in these gases. If the use of CFCs grows at 2.5 percent per year through 2050, CO_2 concentrations grow at the 50th percentile rate defined by the NAS (approximately 0.6 percent per year from 1985 to 2050), N_2O concentrations grow at 0.20 percent per year, and CH_4 concentrations grow at 0.017 ppm per year (approximately 1.0 percent of current concentrations), then equilibrium temperatures would rise by about $5.6^{\circ}C$ by 2075 (relative to observed temperature in 1985), based on a temperature sensitivity of $3^{\circ}C$ for doubled CO_2. Values would be about 50 percent higher for a $4.5^{\circ}C$-based temperature sensitivity and about 50 percent lower for $1.5^{\circ}C$. If CFC use remains constant through 2050, the projected warming would be about $4.3^{\circ}C$ by 2075 ($\pm$ 50%), and if use were phased out by 2010, projected warming would be about $4.0^{\circ}C$ ($\pm$ 50%).

16g. Efforts to gather worldwide time series data for clouds have begun. If adequate, these data may narrow estimates of the cloud contribution to temperature sensitivity within the next decade. However, because of the complexity of this issue, this effort may fail to resolve the large uncertainties affecting this aspect of climate.

17. <u>THE TIMING OF GLOBAL WARMING DEPENDS ON THE RATES AT WHICH GREENHOUSE GASES INCREASE, THE RATES AT WHICH OTHER FORCINGS SUCH AS VOLCANOES AND SOLAR RADIATION CHANGE, AND THE RATE AT WHICH OCEANS TAKE UP HEAT AND PARTIALLY DELAY TEMPERATURE EFFECTS. A GLOBAL WARMING GREATER THAN VARIATIONS THAT OCCURRED THIS PAST CENTURY IS EXPECTED IN THE NEXT TEN YEARS IF VOLCANIC AND SOLAR FACTORS DO NOT SUBSTANTIALLY CHANGE</u> (chapter 6).

17a. The delay in temperature rise introduced by absorption of heat by the oceans can only be roughly estimated. The simple one-dimensional models of oceans that have been used for this purpose do not realistically portray the mechanisms for heat transport into the oceans. Instead, these models use eddy diffusion to treat heat in a parameterized manner so that heat absorption is consistent with data from the paths of transient tracers. These models indicate that the earth will experience substantial delays (on the order of several decades) in experiencing the full warming from greenhouse gases.

17b. The earth's current average temperature is not in equilibrium with the radiative forcing from current concentrations of greenhouse gases. Consequently, global average temperature would increase in the future even if concentrations of gases did not rise any further. For example, if $2^{\circ}C$ is the actual sensitivity of the earth's climate system to a CO_2 doubling, simple models estimate the current "unrealized warming" to be approximately $0.34^{\circ}C$; for a $4^{\circ}C$ temperature sensitivity, the current unrealized warming would be approximately $1.0^{\circ}C$.

17c. Only one three-dimensional general circulation model has been used to simulate changes in temperature as concentrations of greenhouse gases increase over time. This simulation shows a faster warming than predicted by simpler one-dimensional models that use ocean box models to simulate time-dependent warming.

17d. Future uptake of heat by the oceans may change as global warming alters ocean circulation, possibly altering the delaying effect of the oceans as well as reducing their uptake of CO2.

17e. Inadequate information exists to predict how volcanic or solar forcings may change over time. Analyses done of transient warming assume that past levels of volcanic aerosols will continue into the future and that solar forcing changes will average out over relatively short periods of time.

18. <u>WITH A FEW GENERALIZED EXCEPTIONS, THE CLIMATIC CHANGE ASSOCIATED WITH GLOBAL WARMING CANNOT BE RELIABLY PREDICTED ON A REGIONAL BASIS</u> (chapter 6).

18a. In general, as the earth warms, temperature increases will be greater with increasing distance from the equator.

18b. Global warming also can be expected to increase precipitation and evaporation, intensifying the hydrological cycle. While models lack sufficient reliability to make projections for any single region, all perturbation studies with three-dimensional models (general circulation models) show significant regional shifts in dryness and wetness, which suggests that shifts in hydrologic conditions will occur throughout the world.

18c. Current general circulation models represent oceanic, biospheric, and cloud processes with insufficient realism to determine how extreme weather events and climatic norms are likely to change on a regional basis. For example, one analysis of general circulation model outputs suggests that the frequency of extreme climatic conditions will change in many regions of the world. Another model projects increased summer drying in mid-latitudes for perturbation studies, utilizing either of two different representations of clouds. Still another analysis suggests changes in latitudinal gradients of sea surface temperature will play a critical role in determining regional climatic effects.

19. <u>LIMITING GLOBAL WARMING BY REDUCING EMISSIONS OF STRATOSPHERIC PERTURBANTS THAT TEND TO INCREASE OZONE WOULD INCREASE THE STRATOSPHERE'S VULNERABILITY TO OZONE DEPLETION. UNDER SCENARIOS IN WHICH CONTINUED BUFFERING OF OZONE DEPLETION BY OTHER TRACE GASES IS ASSUMED, SUBSTANTIAL GLOBAL WARMING RESULTS</u> (chapter 6).

19a. Decreases in substances with the potential to deplete stratospheric ozone--that is, chlorofluorocarbons and nitrous oxides--would decrease the rate and magnitude of global warming.

19b. Decreases in methane emissions, which have the potential to increase stratospheric and tropospheric ozone and thereby buffer ozone depletion, would decrease warming in three ways: by reducing direct radiative effects from its presence in the troposphere; by lowering water vapor in the stratosphere; and by reducing ozone build-up below 28 km.

19c. Decreases in CO_2 emissions would decrease global warming, but would also have the effect of increasing the stratosphere's vulnerability to ozone depletion.

19d. Decreases in carbon monoxide concentrations, which may occur as energy production practices change, could result in decreases in methane concentrations by increasing OH-radical abundance which, in turn, would shorten the lifetime of methane and could shorten the lifetime of methyl chloroform and CFC-22.

20. ADDITIONAL RESEARCH IS NEEDED ON CLIMATE TO REDUCE UNCERTAINTIES ABOUT GLOBAL WARMING ASSOCIATED WITH TRACE GAS GROWTH (chapter 6).

20a. The key to improving the accuracy of estimates of global temperature sensitivity is to acquire a better understanding of the effect of clouds. This recommendation has been made by numerous groups over the last decade; yet research devoted to this issue remains relatively small.

20b. An increased understanding of ocean circulation is critical to improving estimates of timing and regional projections.

20c. The effect of climate on biological systems and soils and their impact on climate must be modeled if regional estimates of climate change are to be developed.

20d. A better understanding of the radiative properties of CFC-113 and other compounds is needed for estimating the effects of this compound on climate.

20e. Experiments with three-dimensional models that have altered scenarios of vertical ozone need to be undertaken to assess the possible impacts on the magnitude of global warming and on general circulation.

HUMAN HEALTH, WELFARE, AND ENVIRONMENTAL EFFECTS

CHANGES IN COLUMN OZONE ABUNDANCE AND DISTRIBUTION AND A RISE IN GLOBAL TEMPERATURE WOULD BE EXPECTED TO HARM HUMAN HEALTH, WELFARE, AND THE ENVIRONMENT. SOME RISKS CAN BE QUANTIFIED USING RANGES. OTHER RISKS CANNOT BE QUANTIFIED OR DATA NECESSARY FOR QUANTIFICATION ARE AVAILABLE ONLY FOR LIMITED CASE STUDIES.

Ozone shields the earth from UV-B radiation. A decrease in total column ozone will increase this radiation, especially at its most harmful wavelengths. For the DNA action spectrum, a 1 percent depletion would increase the weighted UV flux by about 2 percent. Changes in column ozone and increases in global temperatures could alter many environmental conditions. The findings of this section cover the effects of these changes on human health, ecosystems, crops, materials, air pollution, sea level and other areas that influence human welfare.

FINDINGS

21. BASED ON SURVEYS (PARTICULARLY IN THE UNITED STATES AND IN AUSTRALIA), PROLONGED SUN EXPOSURE IS CONSIDERED TO BE THE DOMINANT RISK FACTOR FOR NONMELANOMA SKIN TUMORS (chapter 7).

21a. Nonmelanoma skin tumors tend to develop in sun-exposed sites (e.g., the head, face, and neck).

21b. Higher incidence rates occur among groups subject to greater exposur to the sun's rays because of occupations that necessitate their working outdoors.

21c. A latitudinal gradient exists for UV-B radiation, and higher incidence rates of nonmelanoma skin tumors generally occur in geographic areas of relatively high UV radiation exposure.

21d. Skin pigmentation provides a protective barrier that reduces the ris of developing nonmelanoma skin tumors.

21e. The risk of nonmelanoma skin tumors is highest among genetically predisposed individuals (e.g., those with xeroderma pigmentosum).

21f. A predisposition to develop nonmelanoma skin tumors exists among light-skinned individuals (skin phenotypes I and II) who are susceptible to sunburn and who have red/blond hair, blue/green eyes, and a Celtic heritage.

22. AVAILABLE EPIDEMIOLOGICAL EVIDENCE INDICATES THAT THE TWO MAJOR TYPES OF NONMELANOMA SKIN TUMORS, SQUAMOUS CELL CARCINOMA (SCC) AND BASAL CELL CARCINOMA (BCC), RESPOND DIFFERENTLY TO SOLAR EXPOSURE. IT HAS BEEN SUGGESTED THAT CUMULATIVE UV RADIATION HAS A GREATER EFFECT ON THE DEVELOPMENT OF SCC THAN ON BCC (chapter 7).

22a. The BCC/SCC incidence ratio decreases with decreasing latitude and therefore, increasing UV levels.

22b. BCC is more likely to develop on normally unexposed sites (e.g., the trunk) compared to SCC.

22c. SCC is more likely than BCC to develop on sites receiving the highest cumulative UV radiation doses (e.g., the nose).

22d. For a given cumulative level of sunlight exposure, the risk of developing SCC may be greater than the risk of developing BCC.

23. THE RESULTS FROM SEVERAL EXPERIMENTAL STUDIES SUGGEST THAT UV-B MAY BE THE MOST IMPORTANT COMPONENT OF SOLAR RADIATION THAT CAUSES VARIATIONS IN THE INCIDENCE OF NONMELANOMA SKIN TUMORS (chapter 7).

23a. UV radiation produces nonmelanoma skin tumors in animals. UV-B wavelengths have been shown to be most effective in producing these tumors.

23b. UV-B has been shown to cause a variety of DNA lesions, to induce neoplastic transformation in cells, and to be a mutagen in both animal and bacterial cells.

24. SEVERAL RESEARCHERS HAVE INVESTIGATED THE CHANGES IN THE INCIDENCE OF NONMELANOMA SKIN TUMORS THAT MAY RESULT FROM INCREASES IN EXPOSURE TO SOLAR UV RADIATION. GIVEN UNCERTAINTIES, RANGES OF ESTIMATES OF INCREASED INCIDENCE THAT COULD OCCUR WITH DEPLETION ARE ESTIMATED (chapter 7).

24a. The action spectra for initiation and promotion of basal cell and squamous cell skin cancer have not been precisely determined. Photocarcinogenic studies indicate that the erythema and DNA action spectra span a range likely to encompass that of squamous cell and basal cell skin cancer. The Robertson-Berger (R-B) meter, while providing useful data for describing ambient UV radiation, does not relate as closely to those wavelengths thought to promote sunburn and skin cancer.

24b. Several studies have provided estimates of a biological amplification factor (BAF), which is defined as the percent change in tumor incidence that results from a 1 percent change in UV-B radiation. The results from six studies produced an overall BAF range that is 1.8-2.85 for all nonmelanoma skin tumors.

24c. BAF estimates are generally higher for males than for females and generally increase with decreasing latitude. In addition, the BAF estimates for SCC are higher than the BAF estimates for BCC. This finding is consistent with observations that the BCC/SCC ratio decreases with decreasing latitude and that BCC is more likely to develop on unexposed sites.

24d. Optical amplification (the change in UV-B radiation related to ozone depletion) increases the response of these cancers to ozone depletion, because the relevant action spectra increase more than 1 percent for a 1 percent depletion. For example, a 1 percent depletion has an optical amplification of over 2 for the DNA action spectrum.

24e. Uncertainty exists in the actual doses of solar UV radiation received by populations and in the statistical estimates of the dose-response coefficients. Therefore, a range of estimates must be developed for changes in incidence associated with changes in dose.

24f. Currently available nonmelanoma mortality data are of uncertain accuracy because of the discrepancy of reporting between death certificates and hospital diagnoses and the low proportion of deaths reported on both hospital diagnoses and death certificates. Based on published studies, the rates of metastasis among SCCs and BCCs have been estimated to be 2-20% and 0.0028-0.55%, respectively. The overall case fatality rate for nonmelanoma skin tumors is approximately 1-2% with three-fourths to four-fifths of the deaths attributable to SCC.

24g. Changes in behavior have tended to increase skin cancer incidence a mortality. While some evidence exists that this is reaching a limi skin cancer rates, even in the absence of ozone depletion, would be likely to rise. Future rates of skin cancer could be reduced if people changed their behavior. Care should be taken, however, in interpreting such a change as a 'cost-free' response.

25. CUTANEOUS MALIGNANT MELANOMA (CMM) IS A SERIOUS LIFE-THREATENING DISEASE THAT AFFECTS A LARGE NUMBER OF PEOPLE IN THE UNITED STATES. THERE ARE SEVERAL HISTOLOGICAL FORMS OF MELANOMA THAT ARE LIKELY TO HAVE SOMEWHAT DIFFERENT ETIOLOGIES AND RELATIONSHIPS TO SOLAR AND UV-B RADIATION (chapte 8).

25a. CMM incidence and mortality is increasing among fair-skinned populations. These increases appear not to be merely the result of improved diagnosis and reporting.

25b. In 1987, it is estimated that there will be an estimated 25,800 case of CMM and 5,800 fatalities related to melanoma in the United States In the absence of ozone depletion, the lifetime risk of CMM in the United States is expected to be about 1 in 150.

26. LIMITATIONS IN THE DATABASE PREVENT ABSOLUTE CERTAINTY ABOUT THE RELATIONSHIP OF SOLAR RADIATION, UV-B, AND CUTANEOUS MALIGNANT MELANOMA (CMM) (chapter 8).

26a. There currently is no animal model in which exposure to UV-B radiation experimentally induces melanomas.

26b. There is also no experimental *in vitro* model for malignant transformation of melanocytes.

26c. No epidemiologic studies of CMM have been conducted in which individual human UV-B exposures (and biologically effective doses of solar radiation) have been adequately assessed.

27. EVALUATION OF THE EPIDEMIOLOGICAL AND EXPERIMENTAL DATABASES FOR MELANOMA REQUIRES CLOSE ATTENTION TO THE RELATIONSHIP OF WAVELENGTH AND DOSE AND TO THE VARIATIONS OF SOLAR RADIATION IN THE AMBIENT ENVIRONMENT (chapter 8).

27a. Ozone differentially removes wavelengths of UV-B between 295 and 320 nm; UV-A (320-400 nm) in wavelengths above 350 nm is not removed, no is visible light (400-900 nm). Ozone removes all UV-C (i.e., wavelengths less than 295 nm).

27b. Wavelengths between 295 nm and 300 nm are generally more biologicall effective (i.e., damage target molecules in the skin, including DNA) than other wavelengths in UV-B and even more so than UV-A radiation.

27c. Latitudinal variations exist in solar radiation; model predictions indicate that the greatest variability is seen in cumulative UV-B (e.g., monthly doses) followed by peak UV-B (highest one-day doses) and then cumulative UV-A. Peak UV-A does not vary significantly across latitudes up to 60°N. Greater ambient variation also exists in UV-B than in UV-A by time of day.

27d. The biologically effective dose of radiation that actually reaches target molecules depends on the duration of exposure at particular locations, time of day, time of year, behavior (i.e., in terms of clothes and sunscreens), pigmentation, and other characteristics of the skin including temporal variations (e.g., changes in pigmentation due to tanning).

27e. Cloudiness and albedo, although causing large variations in the amount of exposure to UV-B and UV-A, do not greatly change the ratio of UV-B to UV-A.

27f. Ozone depletion is predicted to cause the largest increases in radiation in the 295-299 nm UV-B range, less in the 300-320 nm UV-B range; UV-A is virtually unaffected by ozone depletion.

27g. Cutaneous malignant melanoma has a number of different histologic types that vary in their relationship to sunlight, site, racial preference, and possibly in their precursor lesions. Assessment of incidence by types is not consistent among registries, thus complicating attempts to evaluate the relationship between CMM and solar radiation.

27h. Melanin is the principal pigment in skin that gives it color; melanin effectively absorbs UV radiation; the darker the skin, the more the basal layer is protected from UV radiation.

28. A LARGE ARRAY OF EVIDENCE SUPPORTS THE CONCLUSION THAT SOLAR RADIATION IS ONE OF THE CAUSES OF CUTANEOUS MALIGNANT MELANOMA (chapter 8).

28a. Whites, whose skin contains less protective melanin, have higher incidence and mortality rates from CMM than do blacks.

28b. Light-skinned whites, including those who are unable to tan or who tan poorly, have a higher incidence of CMM than do darker-skinned whites.

28c. Sun exposure leading to sunburn apparently induces melanocytic nevi.

28d. Individuals who have more melanocytic nevi have a higher incidence of CMM; the greatest risk is associated with a particular type of nevus -- the dysplastic nevus.

28e. Sunlight induces freckling, and freckling is an important risk factor for CMM.

28f. Incidence has been increasing in cohorts in a manner consistent with changes in patterns of sun exposure, particularly with respect to increasing intermittent exposure of certain anatomical sites.

28g. Immigrants who move to sunnier climates have higher rates of CMM than populations who remain in their country of origin. Immigrants develop rates approaching those of prior (but native born) immigran to the adopted country; this is particularly accentuated in individuals arriving before the age of puberty (10-14 years).

28h. It has been suggested that CMM risk may be associated with childhoo sunburn; other evidence suggests that childhood sunburn may reflect an individual's pigmentary characteristics or may be related to nev development, rather than being a separate risk factor.

28i. Most studies that have used latitude as a surrogate for sunlight or UV-B exposure have found an increase in the incidence or mortality CMM correlated to proximity to the equator. A recent study of incidence using measured UV-B and CMM survey data found a strong relationship between UV-B and incidence of CMM. Another study that used modeled UV-B data and an expanded database on mortality found strong UV-B/mortality relationship.

28j. One form of CMM, Hutchinson's melanotic freckle, appears almost invariably on the chronically sun-damaged skin of older people.

29. SOME EVIDENCE CREATES UNCERTAINTY ABOUT THE RELATIONSHIP BETWEEN SOLAR RADIATION AND CUTANEOUS MALIGNANT MELANOMA (chapter 8).

29a. Some ecologic epidemiology studies, primarily in Europe or close to the equator, have failed to find a latitudinal gradient for CMM.

29b. Outdoor workers generally have lower incidence and mortality rates for CMM than indoor workers, which appears incompatible with a hypothesis that cumulative dose from solar exposure causes CMM.

29c. Unlike basal cell and squamous cell carcinomas, most CMM occurs on sites that are not habitually exposed to sunlight; this contrast suggests that cumulative exposure to solar radiation or UV-B is not solely responsible for variations in CMM.

30. UV-B RADIATION IS A LIKELY COMPONENT OF SOLAR RADIATION THAT CAUSES CUTANEOUS MALIGNANT MELANOMA (CMM), EITHER THROUGH INITIATION OF TUMORS OR THROUGH SUPPRESSION OF THE IMMUNE SYSTEM (chapter 8).

30a. Xeroderma pigmentosum patients who fail to repair UV-B-induced pyrimidine dimers in their DNA have a 2,000-fold excess rate of CMM by the time they are 20.

30b. UV-B is the most active part of the solar spectrum in the induction of mutagenesis and transformation *in vitro*.

30c. UV-B is the most active part of the solar spectrum in the induction of carcinogenesis in experimental animals and is considered by most to be a causative agent of nonmelanoma skin cancer in humans.

30d. UV-B is the most active portion of the solar spectrum in inducing immunosuppression, which may have a role in melanoma development.

30e. The limitations in the epidemiologic and experimental database leave some doubt as to the effectiveness of UV-B wavelengths in causing CMM.

31. WHILE UNCERTAINTY EXISTS, INCREASES IN THE INCIDENCE AND MORTALITY OF CUTANEOUS MALIGNANT MELANOMA ARE LIKELY AS A RESULT OF OZONE DEPLETION. WHILE MANY UNCERTAINTIES EXIST (E.G., REGARDING ACTION SPECTRA, PEAK VERSUS CUMULATIVE DOSE, ETC.) ABOUT THE NATURE OF THE RELATIONSHIP BETWEEN UV-B AND MELANOMA, THE FACT THAT UV-B RADIATION VARIES ACROSS THE ENVIRONMENT IN THE RANGE OF VARIATION EXPECTED FROM DEPLETION PROVIDES INFORMATION USUALLY UNAVAILABLE TO RESEARCHERS MAKING QUANTITATIVE RISK ESTIMATES. THUS ALTHOUGH IMPERFECT, EPIDEMIOLOGIC INFORMATION EXISTS TO ESTIMATE A RANGE OF CHANGES IN INCIDENCE AND MORTALITY IF THE OZONE LAYER IS DEPLETED (chapter 8).

31a. Uncertainty exists about the appropriate action spectrum to be used in estimating dose, the best functional form for dose-response, and the best way to characterize dose (peak value, cumulative summer exposure, etc.). Histologically different CMMs (or possibly CMM located at different anatomical sites) are likely to have different dose-response relationships. Most estimates of CMM dose-response relationships fail to consider these histological or site differences. Nonetheless, by encompassing a range of possibilities, it is possible to estimate dose-response because of the systematic variations in UV-B.

31b. A recent study by the NIH presents a well-designed ecological study of melanoma and UV-B using survey data and measured UV-B at ground level. While uncertainties exist, this dose-response relationship, when used with different action spectra and assumptions about the importance of peak versus cumulative exposure, can be utilized to estimate a range of values for cases. The relationship estimates that a 1 percent change in ozone is likely to increase incidence by between slightly less than 1 to 2 percent, depending on the choice of action spectrum. The appropriate action spectrum is likely to be encompassed in the range of erythema and DNA.

31c. Melanoma mortality is estimated at about 25 percent of all cases. This result is consistent with the projections of a dose-response model of mortality developed by EPA/NCI. It is estimated that a 1 percent change in ozone would result in between a 0.3 and a 2.0 percent change in CMM mortality depending on the assumptions about the appropriate dose and UV weighting functions used in the model.

31d. Additional uncertainties for projecting future incidence and mortality of CMM in the U.S. include the lack of an adequate database describing variations in skin pigmentation and human sun-exposure behavior among different populations and estimates of how these relationships may change in the future.

32. UV-B SUPPRESSES THE IMMUNE SYSTEM IN ANIMAL EXPERIMENTS (chapter 9).

32a. UV radiation administered at relatively low doses causes a depression in local contact hypersensitivity (a form of cell-mediated immunity) resulting from an inability to respond to an antigen presented through UV-irradiated skin.

32b. High doses of UV radiation cause a depression in systemic contact and delayed type hypersensitivity reactions, that result in an inability of the animal to respond to an antigen which is presented to the animal through unirradiated skin.

32c. Both the local and systemic effects on contact hypersensitivity are mediated by a T suppressor cell which prevents the development of active immunity to the antigen.

32d. The immunosuppressive effects of ultraviolet radiation (UVR) have been found to reside almost entirely in the UV-B portion of the ground level solar radiation.

33. SUPPRESSION OF THE IMMUNE SYSTEM MAY PLAY AN IMPORTANT ROLE IN CARCINOGENESIS (chapter 9).

33a. Animals which are UV-irradiated develop T suppressor cells which interfere with the immune response to UV-induced tumors in such a way that the animals are more susceptible to the growth of autochthonous UV-induced tumors. The contribution of the suppression of the immune system to cancer incidence that would result from ozone depletion is reflected in the dose-response estimates of photocarcinogenesis assuming that the action spectra for the two phenomena are the same. If these two impacts have different action spectra, the estimates could be either high or low.

34. LIMITED EXPERIMENTAL DATA INDICATE UV-B SUPPRESSES THE HUMAN IMMUNE SYSTEM (chapter 9).

34a. Although there is limited information about the effects of UV radiation on humans, several studies indicate that the immune response of humans is depressed by UV radiation and is depressed in UV-irradiated skin.

35. UV-B-INDUCED SUPPRESSION OF THE HUMAN IMMUNE SYSTEM COULD HAVE A DELETERIOUS EFFECT WITH REGARD TO MANY HUMAN DISEASES (chapter 9).

35a. Preliminary studies indicate that UV radiation may prevent an effective immune response to micro-organisms that infect via the skin, thus predisposing to reexpression or chronic infection.

35b. Two human diseases that may be influenced by UV-B-induced immune suppression are herpes virus infections and leishmaniasis.

35c. Almost no research has been conducted on the influence of UV-B on other infectious diseases; additional investigation is clearly warranted.

35d. For at least one theory of the mechanisms of UV-B-induced suppression of the immune system (that involving urocanic acid), a possibility exists that non-whites, as well as whites, would be vulnerable to increased immune suppression caused by ozone depletion.

35e. Because UV-B can produce systemic immunologic change, the possibility exists that changes in UV-B could have resulted in effects on diseases whose control requires systemic rather than local immunity.

35f. Immunologic studies to date have not assessed the effects of long-term, low-dose UV-B irradiation. Consequently, the magnitude of this risk cannot be assessed.

36. EVIDENCE EXISTS SUGGESTING THAT CATARACT INCIDENCE WILL CHANGE WITH ALTERATIONS IN THE FLUX OF UV-B CAUSED BY OZONE DEPLETION (chapter 10).

36a. Many possible mechanisms exist for formation of cataracts. UV-B may play an important role in some mechanisms.

36b. Although the cornea and aqueous humor of the human eye screen out significant amounts of UV-A and UV-B radiation, nearly 50 percent of radiation at 320 nm is transmitted to the lens. Transmittance declines substantially below 320 nm, so that less than 1 percent is transmitted below approximately 290 to 300 nm. However, the results of laboratory experiments on animals indicate that short wavelength UV-B (i.e., below 290 nm) is perhaps 250 times more effective than long wavelength UV-B (i.e., 320 nm) in inducing cataracts.

36c. Human cataract prevalence varies with latitude and UV radiation; brunescent nuclear cataracts show the strongest relationship.

37. INCREASES IN THE AMOUNT OF UV-B THAT CAN REACH THE RETINA APPEAR CAPABLE OF CAUSING STABLE RETINAL DISORDERS AND RETINAL DEGENERATION, TWO CAUSES OF BLINDNESS (chapter 10).

38. LIMITED STUDIES ANALYZING THE EFFECT OF INCREASED UV-B RADIATION ON CROPS GENERALLY SHOW ADVERSE IMPACTS. HOWEVER, CONCLUSIONS ABOUT THE AMOUNT OF YIELD LOSSES ATTRIBUTABLE TO UV-B CANNOT BE DRAWN (chapter 11).

38a. Difficulties in experimental design, the large number of species and cultivars, and complex interactions between plants and their environment have prevented quantification of total crop loss from increases in UV-B.

38b. Action spectra for UV damage to higher plants are limited, but indicate a strong weighting toward shorter UV-B wavelengths which are those most affected by ozone reduction.

39. OF PLANT CULTIVARS TESTED IN THE LABORATORY, APPROXIMATELY 70 PERCENT WERE DETERMINED TO BE SENSITIVE TO UV-B; CARE MUST BE TAKEN IN INTERPRETING THIS FINDING (chapter 11).

39a. Different cultivars within a species have exhibited different degrees of UV-B sensitivity. While this suggests selective breeding could limit damage, neither the basis for selectivity nor the potential effect on other aspects of growth has been studied.

39b. Laboratory experiments have been shown to inadequately replicate effects in the field, thus the implications of cultivar sensitivity are not certain.

39c. In some species, mitigation responses more readily apparent in the field (e.g., increased production of UV absorbing flavonoids) have reduced adverse impacts.

40. THE EFFECTS OF UV-B RADIATION HAVE BEEN EXAMINED FOR ONLY FOUR OF THE TEN MAJOR TERRESTRIAL ECOSYSTEMS AND FOR ONLY A THIRD OF THE PLANT GROWTH FOR[M] (chapter 11).

40a. Little or no data exist on enhanced UV-B effects on trees, woody shrubs, vines, or lower vascular plants.

41. LARGE UNCERTAINTIES EXIST AS A RESULT OF AN IMPERFECT EXPERIMENTAL DESIGN OR DOSIMETRY. EXISTING EXPERIMENTAL FIELD DATA SUGGEST A POTENTIAL REDUCTION IN CROP YIELD FOR SOME CROPS DUE TO ENHANCED UV-B RADIATION (chapter 11).

41a. Field experiments in which UV-B radiation has been supplemented are limited. Several of the earlier field experiments are of limited value since UV-B doses or other factors such as soil temperature we[re] not sufficiently controlled or representative of field conditions. Dose-response studies in the field are particularly different.

41b. The only long-term field studies of a crop involved soybeans. These studies have found that enhanced levels of UV-B, simulating between 16 and 25 percent ozone depletion, caused crop yield reductions of u[p] to 25 percent in a particular cultivar. Smaller reductions in yiel[d] were experienced in years where drought conditions existed.

41c. Soybean (CV Essex) yield could be accurately predicted when total UV-B dose, daily maximum temperature, and number of days of precipitation were included in a regression model.

41d. The lipid and protein content of soybean was reduced up to 10 percent; however, higher UV-B doses alone did not consistently resul[t] in the largest reductions.

41e. While only several cultivars have been tested in the field, two out of three soybean cultivars tested under laboratory conditions were sensitive to UV-B. If this relationship holds true in the field, it suggests (when considered in light of yield reduction experiments) that UV-B increases could harm the potential of the world agricultural system to produce soybeans.

42. THE EFFECTS OF UV-B ON FUNGAL OR VIRAL PATHOGENS VARY WITH PATHOGEN, PLANT SPECIES, AND CULTIVAR (chapter 11).

42a. Current evidence on possible interactions with pathogens is very limited.

42b. Reduced vigor in UV-sensitive plants could render the plants more or less susceptible to pest or disease damage and thus result in changes in crop yield.

43. CHANGES IN UV-B LEVELS MAY INDUCE SHIFTS IN INTERSPECIFIC COMPETITION (chapter 11).

43a. If enhanced UV-B favors weeds over crops, agricultural costs (e.g., for increased tilling and herbicide application) could increase. However, insufficient evidence exists to form a basis for evaluating this effect.

43b. Increases in UV-B could alter the results of the competition in natural ecosystems and thus shift community composition. Since UV-B changes would be both global and long term, possible UV-induced alterations of plant species balances could result in large-scale changes in the character and equilibrium of vegetation in nonagricultural areas such as forests and grasslands.

44. UV-B RADIATION INHIBITS AND STIMULATES FLOWERING, DEPENDING ON THE SPECIES AND GROWTH CONDITIONS (chapter 11).

44a. The timing of flowering may also be influenced by UV-B radiation, and there is limited evidence that pollen may be susceptible to UV damage upon germination.

44b. Reproductive structures enclosed within the ovary appear to be well-protected from UV-B radiation.

45. INTERACTIONS BETWEEN UV-B RADIATION AND OTHER ENVIRONMENTAL FACTORS ARE IMPORTANT IN DETERMINING POTENTIAL UV-B EFFECTS ON PLANTS (chapter 11).

45a. UV-B effects may be worsened under low light regimes or less apparent under conditions of limited nutrients or water.

45b. Interactions with other environmental effects make extrapolation of data from growth chambers or greenhouses to field conditions difficult and often unreliable.

45c. The combined effect of higher UV-B and other environmental changes cannot be adequately assessed by current data. Extensive, long-term studies would be required.

46. INITIAL EXPERIMENTS SHOW THAT REDUCTIONS IN STRATOSPHERIC OZONE, WHICH INCREASES SOLAR ULTRAVIOLET RADIATION, HAVE THE POTENTIAL TO HARM AQUATIC LIFE. DIFFICULTIES IN EXPERIMENTAL DESIGNS AND THE LIMITED SCOPE OF THE STUDIES PREVENT THE QUANTIFICATION OF RISKS (chapter 12).

46a. Increases in energy in the 290-320 nm wavelengths that would occur if the ozone layer were depleted could harm aquatic life.

46b. Various experiments have shown that UV-B radiation damages fish larvae and juveniles, shrimp larvae, crab larvae, copepods, and plants essential to the marine food web.

46c. Up to some threshold level of exposure, most zooplankton show no effect due to increased exposure to UV-B radiation. However, exposure above the dose threshold elicits significant and irreversible physiological and behavioral effects.

46d. While the exact limits of tolerance and current exposure have not been precisely determined, estimates of these two properties for a variety of aquatic organisms show them to be essentially equal.

46e. The equality of tolerance and exposure suggests that solar UV-B radiation is currently an important limiting ecological factor, and the sunlight-exposed organisms sacrifice potential resources to avoid increased UV-B exposure. Thus, even small increases of UV-B exposure would be likely to further injure species currently under UV-B stress.

46f. A decrease in column ozone is reasonably likely to diminish the time that zooplankton can survive or breed at or near the surface of waters they inhabit. For some zooplankton, the time they spend at or near the surface is critical for breeding. Whether the population could endure a significant shortening of surface time is unknown.

46g. Sublethal exposure of copepods produces a reduction in fecundity.

46h. Of the animals tested, no zooplankton possess a sensory mechanism for directly detecting UV-B radiation; therefore, it would be unlikely that they would actively avoid enhanced levels of exposure resulting from a reduction in column ozone.

46i. Exposure of a community to UV-B stress in controlled experiments has resulted in a decrease in species diversity, and therefore a possible reduction in ecosystem resilience and flexibility.

46j. One experiment predicted an 8 percent annual loss of the larval anchovy population from a 9 percent reduction in column ozone in a marine system with a 10-meter mixed layer.

47. IN COMMON WITH ALL OTHER LIVING ORGANISMS, THE AQUATIC BIOTA COPE WITH SOLAR UV-B RADIATION BY AVOIDANCE, [illegible], AND REPAIR MECHANISMS. UNCERTAINTY EXISTS AS TO THE EXTENT TO WHICH SUCH MITIGATION MECHANISMS WOULD OCCUR (chapter 12).

48. DETERMINATION OF UV-B EXPOSURE IN AQUATIC SYSTEMS IS COMPLEX BECAUSE OF THE VARIABLE ATTENUATION OF UV-B RADIATION IN THE WATER COLUMN (chapter 12).

48a. Because aquatic organisms are small and do not usually have fixed locations, it is very difficult to obtain accurate data needed to model the systems and verify results. Current understanding of the life cycle of organisms is very limited.

49. ABOUT ONE HALF OF THE WORLD'S PROTEIN IS DERIVED FROM MARINE SPECIES. IN MANY THIRD WORLD COUNTRIES, THIS PERCENTAGE IS LARGER. RESEARCH IS NEEDED TO IMPROVE OUR UNDERSTANDING OF HOW OZONE DEPLETION COULD INFLUENCE THESE SYSTEMS (chapter 12).

49a. A comprehensive analysis of sublethal and lethal effects of solar UV on littoral, benthos, and planktonic ecosystems is needed.

49b. A model of energy flow analysis leading to protein production where solar input is augmented by increased ultraviolet radiation would be required to better evaluate potential effects. Marine organisms responses to projected increases in UV must be considered in the context of the oceans as a dynamic moving fluid.

49c. Better documentation of the effects of present levels of ultraviolet light on marine organisms is needed.

49d. Intensive research is needed to identify biochemical indices that reflect UV stress in marine organisms.

50. INCREASED UV-B RADIATION WILL ACCELERATE THE DEGRADATION OF POLYMERS (chapter 13).

50a. Several commercial polymers (e.g., polyethylene, polypropylene, poly(vinylchloride)), although theoretically UV transparent, contain chromophore impurities that absorb light in the UV-B region of the spectrum. Other polymers (e.g., polycarbonate) have structural features in their molecules that result in strong UV-B light absorption.

50b. Several polymers have important outdoor applications (e.g., used in siding and window glazing in the building industry, in film and containers in packaging, in housewares and toys, and in paints and protective coatings). Such polymers are likely to be exposed to significant amounts of UV-B radiation. Other polymers are stored outside before use and could deteriorate during these periods.

50c. Absorption of UV-B radiation in polymers causes photo-induced reactions and alters important mechanical, physical, or optical properties of the polymers (e.g., yellowing, brittleness) and thus degrades (i.e., reduces the useful life of) the polymers.

51. INCREASED USE OF UV-STABILIZERS FOR PROTECTION OF POLYMERS AGAINST UV RADIATION WOULD HAVE NEGATIVE EFFECTS (chapter 13).

51a. Increased amounts of stabilizers might adversely affect the processing and use properties of some polymers (e.g., hardness, thermal conductivity, flow characteristics). For example, increased amounts of titanium dioxide in poly(vinylchloride) might affect its processing properties, increasing its costs of production.

51b. Changes in the amount of stabilizer (and other additives) would increase costs of products. Alternatively, manufacturers could develop new formulations to avoid or minimize impurities in production.

51c. The addition of stabilizers to polymers may be limited by practical problems of material characteristics or manufacture. However, other responses may be possible to limit damage.

52. INCREASED UV-B RADIATION DUE TO OZONE DEPLETION COULD HAVE ADVERSE ECONOMIC EFFECTS (chapter 13).

52a. Changes in polymer processing properties can result in more equipment shutdowns, higher maintenance costs, and increased utility costs.

52b. Increased operating costs and material costs (e.g., for stabilizers, lubricants, and other additives) would have an adverse economic impact on the polymer/plastic and related industries.

52c. In a case study using preliminary data and methods, and a given scenario of ozone depletion (26% depletion by 2075), undiscounted cumulative (1984-2075) economic damage for poly(vinylchloride) is estimated at $4.7 billion (USA only). Due to the lack of data, possible damage to other polymers has not been assessed.

53. POTENTIAL DAMAGES TO POLYMERS RELATED TO OZONE DEPLETION AND CLIMATE CHANGE ARE DIFFICULT TO ESTIMATE (chapter 13).

53a. Due to lack of relevant experimental data, only approximate estimation methods are available to determine the potential extent of light-induced damage to polymers and other materials.

53b. Depending upon the chemical nature of a polymer, the components of the compound, and the weathering factors, both temperature and humidity tend to increase the rate of degradation.

53c. Research on dose-response relationships for polymers could increase our ability to project the effects of ozone depletion.

53d. Actual action spectra need to be developed for different polymers.

53e. The feasibility of different mitigation measures needs to be experimentally determined.

53f. The synergistic effects of increased humidity and temperature need to be considered.

54. RESULTS FROM ONE MODELING STUDY AND ONE CHAMBER STUDY SUGGEST THAT INCREASED ULTRAVIOLET RADIATION FROM OZONE DEPLETION MAY INCREASE THE RATE OF TROPOSPHERIC OZONE FORMATION (chapter 14).

54a. According to these studies, increases in UV-B associated with ozone depletion would increase the quantity of ground-based ozone associated with various hydrocarbon and nitrogen oxides emission levels. Results for individual cities vary, depending on the city's location and on the exact nature of the pollution.

54b. According to these studies, global warming would enhance the effects of increased UV-B radiation on the formation of ground-based ozone.

54c. According to these studies, ground-based ozone would form closer to urban centers. This would cause larger populations in some cities to be exposed to peak values.

54d. More research is needed to verify and expand the results of these initial studies.

55. PRELIMINARY RESULTS FROM ONE STUDY ALSO SUGGEST THAT LARGE INCREASES IN HYDROGEN PEROXIDE WOULD RESULT FROM INCREASED UV-B RADIATION (chapter 14).

55a. If hydrogen peroxide increases as predicted in this study, the oxidizing capability potential of the atmosphere, including the formation of acid rain, would be influenced.

55b. More research, especially a chamber study, is needed to verify this effect.

56. INCREASES IN GROUND-BASED OZONE WOULD ADVERSELY AFFECT PUBLIC HEALTH AND WELFARE (chapter 14).

56a. If UV-B increases enhanced ozone production, more U.S. cities would be unable to meet health-based ground-level ozone standards, and background ozone would increase.

56b. Crops, ecosystems, and materials would be adversely affected by increased ground-level ozone.

57. THE PROJECTED GLOBAL WARMING WOULD ACCELERATE THE CURRENT RATE OF SEA LEVEL RISE BY EXPANDING THE DENSITY OF OCEAN WATER, MELTING ALPINE GLACIERS, AND EVENTUALLY INCREASING THE RATE AT WHICH POLAR ICE SHEETS MELT OR DISCHARGE ICE INTO THE OCEANS (chapter 15).

58. GLOBAL AVERAGE SEA LEVEL APPEARS TO HAVE RISEN 10 TO 15 CM OVER THE LAST CENTURY (chapter 15).

58a. Studies of the possible contribution of thermal expansion and alpine meltwater to sea level rise, based on the $0.6^{\circ}C$ warming of the past century, indicate that these two sources are insufficient to explain the estimated sea level rise that has occurred during this period. Consequently, some other source, such as melting of the polar ice caps, must be considered a possibility.

59. ESTIMATES OF THE RISE IN SEA LEVEL THAT COULD TAKE PLACE IF MEASURES TO LIMIT THE GLOBAL WARMING ARE NOT UNDERTAKEN RANGE FROM 10 TO 20 CM BY THE YEAR 2025 AND 50 TO 200 CM BY 2100 (chapter 15)

59a. According to published studies, thermal expansion of the oceans alone would increase sea level rise between about 30 cm and 100 cm by 2100, depending on the realized temperature change. This is the most certain contribution.

59b. Melting of alpine glaciers and possibly of ice on Greenland could each contribute 10 to 30 cm through 2100, depending on the scenario. This contribution also has a high degree of likelihood.

59c. The contribution of Antarctic deglaciation is more difficult to project. It has been estimated at between 0 and 100 cm; however, the possibilities cannot be ruled out that (1) increased snowfall could increase the size of the Antarctic ice sheet and thereby partially offset part of the sea level rise from other sources; or (2) meltwater and enhanced calving of the ice sheet could increase the contribution of Antarctic deglaciation to as much as 2 m. The Antarctic contribution to sea level rise may be more sensitive to time delays after certain threshold conditions are reached than to the magnitude of total warming.

60. <u>OVER THE MUCH LONGER TERM (THE NEXT FEW CENTURIES) DISINTEGRATION OF THE WEST ANTARCTIC ICE SHEET MIGHT RAISE SEA LEVEL BY 6 METERS</u> (chapter 15).

60a. If a disintegration takes place, glaciologists generally believe th such a complete disintegration of the west Antarctic ice sheet woul take at least 300 years, and probably at least 500 years.

60b. A global warming might result in sufficient thinning of the Ross an Filcher-Ronne Ice Shelves in the next century to make the process o disintegration irreversible.

61. <u>LOCAL TRENDS IN SUBSIDENCE AND EMERGENCE MUST BE ADDED OR SUBTRACTED TO GLOBAL RISK ESTIMATES IN ORDER TO ESTIMATE RELATIVE SEA LEVEL RISE AT PARTICULAR LOCATIONS</u> (chapter 15).

61a. Most of the Atlantic and Gulf Coasts of the United States--as well the Southern Pacific coast--are subsiding 10-20 cm per century.

61b. Louisiana is subsiding 1 m per century, while parts of Alaska are emerging 10-150 cm per century.

61c. Due to subsidence already occurring in areas such as Bangladesh, Bangkok, and the Nile delta, these areas are extremely vulnerable t sea level rise.

62. <u>A SUBSTANTIAL RISE IN SEA LEVEL WOULD PERMANENTLY INUNDATE WETLANDS AND LOWLANDS, ACCELERATE COASTAL EROSION, EXACERBATE COASTAL FLOODING, AND INCREASE THE SALINITY OF ESTUARIES AND AQUIFERS</u> (chapter 15).

62a. Louisiana is the state most vulnerable to a rise in sea level. Important impacts would also occur in Florida, Maryland, Delaware, New Jersey, and in the coastal regions of other states.

62b. A rise in sea level of 1 to 2 m by the year 2100 could destroy 50 percent to 80 percent of U.S. coastal wetlands.

62c. Limited studies predict that increased salinity from sea level rise would convert cypress swamps to open water and threaten drinking water supplies in areas such as Louisiana, Philadelphia, and New Jersey. Other areas, such as Southern Florida, may also be vulnerable but have not been investigated.

62d. Studies of Bangladesh and the Nile River Delta indicate that these river deltas, which are already subsiding, would be greatly affecte by rising sea level, experiencing significant economic and environmental losses.

63. EROSION PROJECTED IN VARIOUS STUDIES TO RESULT FROM ACCELERATED SEA LEVEL RISE COULD THREATEN U.S. RECREATIONAL BEACHES (chapter 15).

63a. Case studies of beaches in New Jersey, Maryland, California, South Carolina, and Florida have concluded that a 30-cm rise in sea level would result in beaches eroding 20-60 m or more. Major beach preservation efforts would be required if recreational beaches are to be maintained.

64. ACCELERATED SEA LEVEL RISE WOULD INCREASE THE DAMAGES FROM FLOODING IN COASTAL AREAS (chapter 15).

64a. Flood damages would increase because higher water levels would provide a higher base for storm surges.

64b. Erosion would increase the vulnerability to storm waves, and decreased natural and artificial drainage would increase flooding during rainstorms.

65. ESTIMATES OF DAMAGE FROM SEA LEVEL RISE MUST CONSIDER POSSIBLE MITIGATION BY HUMAN RESPONSES (chapter 15).

65a. The adverse impacts of sea level rise could be ameliorated through anticipatory land use planning and structural design changes.

65b. In a case study of two cities, Charleston, South Carolina, and Galveston, Texas, accelerated anticipatory planning was estimated to reduce net damages by 20 to 60 percent.

66. RELATED IMPACTS OF A GLOBAL WARMING WOULD ALSO AFFECT IMPACTS OF SEA LEVEL RISE (chapter 15).

66a. Increased droughts might amplify the salinity impacts of sea level rise.

66b. Increased hurricanes and increased rainfall in coastal areas could amplify flooding from sea level rise.

66c. Warmer temperatures might impair peat formation of salt marshes and would enable mangrove swamps to take over areas that are presently salt marsh.

66d. Decreased northeasters might reduce damage.

67. RESEARCH OPPORTUNITIES EXIST TO IMPROVE SEA LEVEL RISE ESTIMATES AND IMPACTS (chapter 15).

67a. The most critical areas of research for reducing the variation in estimates of future sea level rise are ice melting and runoff in Antarctica and Greenland and ice discharge.

67b. Research in glacial discharge in Antarctica should focus not just on West Antarctica, but on Pine Island and East Antarctica.

67c. An improved program of tidal gauge stations, especially in the southern hemisphere, and satellite altimetry should be used to measure sea level rise and the mass balance of ice sheets.

68. CLIMATE CHANGE HAS HAD A SIGNIFICANT IMPACT ON FORESTS IN THE PAST. IF CURRENT PREDICTIONS PROVE ACCURATE, THERE IS A POTENTIAL FOR DRAMATIC SHIFTS IN FORESTS AND VEGETATION OVER THE NEXT 100 YEARS (chapter 16).[4]

68a. Climate models predict that a global warming of approximately 1.5°C to 4.5°C will be induced by a doubling of atmospheric CO2 and other trace gases during the next 50 to 100 years. The period 18,000 to 0 years B.P. is the only general analog for a global climate change of this magnitude. The geological record from this glacial to inter-glacial interval provides a basis for qualitatively understanding how vegetation may change in response to large climatic change.

68b. The paleovegetational record shows that climatic change as large as that expected to occur in response to CO2 doubling is likely to induce significant changes in the composition and patterns of the world's biomes. Changes of 2°C to 4°C have been significant enough to alter the composition of biomes, and to cause new biomes to appear and others to disappear. At 18,000 B.P., the vegetation in eastern North America was quite distinct from that of the present day. The cold, dry climate of that time seems to have precluded the widespread growth of birch, hemlock, beech, alder, hornbeam, ash, elm, and chestnut, all of which are fairly abundant in present-day deciduous forest. Southern pines were limited to grow with oak and hickory in Florida.

68c. Available paleoecological and paleoclimatological records do not provide an analog for the high rate of climate change and unprecedented global warming predicted to occur over the next century. Previous changes in vegetation have been associated with climates that were nearly 5°C to 7°C cooler and took thousands of years to evolve rather than decades, the time during which such changes are now predicted to occur. Insufficient temporal resolution (e.g., via radiocarbon dates) limits our ability to analyze the decadal-scale rates of change that occurred prior to the present millennium.

68d. Limited experiments conducted with dynamic vegetation models for North America suggest that decreases in net biomass may occur and that significant changes in species composition are likely. Experiments with one model suggest that eastern North American biomass may be reduced by 11 megagrams per hectare (10% of live biomass) given the equivalent of a doubled CO2 environment. Plant taxa will respond individualistically rather than as whole communities to regional changes in climate variables. At this time such analyses must be treated as only suggestive of the kinds of

[4] Findings 68 to 71 are summarized from Appendix B, which provides a comprehensive review of potential impacts of global climate change.

change that could occur. Many critical processes are simplified or omitted and the actual situation could be worse or better.

68e. Future forest management decisions in major timber-growing regions are likely to be affected by changes in natural growing conditions. For example, one study suggests that loblolly pine populations are likely to move north and northeast into Pennsylvania and New Jersey, while its range shrinks in the west. The total geographic range of the species may increase, but a net loss in productivity may result because of shifts to less accessible and less productive sites. While the extent of such changes is unclear, adjustments will be needed in forest technology, resource allocation, planning, tree breeding programs, and decision-making to maintain and increase productivity.

68f. Dynamic vegetation models based on theoretical descriptions of all factors that could influence plant growth must be improved and/or developed for all major kinds of vegetation. In order to make more accurate future predictions, these models must be validated using the geological record and empirical ecological response surfaces. In particular, the geological record can be used to test the ability of vegetation models to simulate vegetation that grew under climate conditions unlike any of the modern day conditions.

68g. Dynamic vegetation models should incorporate direct effects of atmospheric CO2 increases on plant growth and other air pollution effects. Improved estimates of future regional climates are also required in order to make accurate predictions of future vegetation changes.

69. LIMITED ASSESSMENTS SUGGEST THAT IMPORTANT CHANGES IN AGRICULTURE AND FARM PRODUCTIVITY ARE LIKELY THROUGHOUT THE WORLD IF CLIMATE CHANGE OCCURS AS PREDICTED. ESTIMATES OF IMPACTS ON SPECIFIC REGIONS ARE DIFFICULT TO MAKE BECAUSE REGIONAL PROJECTIONS OF CHANGE CANNOT BE RELIABLY MADE. CURRENT CLIMATIC KNOWLEDGE IS ONLY SUFFICIENT TO SUPPORT VULNERABILITY STUDIES FOR ALTERNATIVE SCENARIOS (chapter 16).

69a. Climate has had a significant impact on farm productivity and geographical distribution of crops. Examples include the 1983 drought, which contributed to a nearly 30 percent reduction in corn yields in the U.S.; the persistent Great Plains drought between 1932-1937, which contributed to nearly 200,000 farm bankruptcies; and the climate shift of the Little Ice Age (1500-1800), which led to the abandonment of agricultural settlements in Scotland and Norway.

69b. World agriculture is likely to undergo significant shifts if trace-gas-induced climate warming in the range of 1.5°C to 4.5°C occurs over the next 50 to 100 years. Climatic effects on agriculture will extend from local to regional and international levels. However, modern agriculture is very dynamic and is constantly responding to changes in production, marketing, and government programs.

69c. The main effects likely to occur at the field level will be physical impacts of changes in thermal regimes, water conditions, and pest infestations. High temperatures have caused direct damage to crops such as wheat and corn; moisture stress, often associated with elevated temperatures, is harmful to corn, soybean, and wheat during flowering and grain fill; and increased pests are associated with higher, more favorable temperatures.

69d. Even relatively small increases in the mean temperature can increase the probability of harmful effects in some regions. Analysis of historical data has shown that an increase of 1.7°C (3°F) in mean temperature changes by about a factor of three the likelihood of a five-consecutive-day maximum temperature event of at least 35°C (95°F) occurring in a city like Des Moines. In regions where crops are grown close to their maximum tolerance limits, extreme temperature events may have significant harmful effects on crop growth and yield.

69e. Limited experiments using climate scenarios and agricultural productivity models have demonstrated the sensitivity of agricultural systems to climate change. Future farm yields are likely to be affected by climate because of changes in the length of the growing season, heating units, extreme winter temperatures, precipitation, and evaporative demand. In addition, field evaluations show that total productivity is a function of the drought tolerance of the land and the moisture reserve, the availability of land, the ability of farmers to shift to different crops, and other factors.

69f. The transition costs associated with adjusting to global climatic change are not easily calculated, but are likely to be very large. Accommodating to climate change may require shifting to new lands and crops, creating support services and industries, improving and relocating irrigation systems, developing new soil management and pest control programs, and breeding and introducing new heat- or drought-tolerant species. The consequences of these decisions on the total quantity, quality, and cost of food are difficult to predict.

69g. Current projections of the effects of climate change on agriculture are limited because of uncertainties in predicting local temperature and precipitation patterns using global climate models, and because of the need for improved research studies using controlled atmospheres, statistical regression models, dynamic crop models and integrated modeling approaches.

70. WATER RESOURCE SYSTEMS HAVE UNDERGONE IMPORTANT CHANGES AS THE EARTH'S CLIMATE HAS SHIFTED IN THE PAST. CURRENT ANALYSES SUGGEST AN INTENSIFIED HYDROLOGIC CYCLE, IF CLIMATE CHANGE OCCURS AS PREDICTED (chapter 16).

70a. There is evidence that climate change since the last ice age (18,000 years B.P.) has significantly altered the location of lakes -- although the extent of present day lakes is broadly comparable with 18,000 years B.P. For example, there is evidence indicating the existance of many tropical lakes and swamps in the Sahara, Arabian, and Thor Deserts around 9,000 to 8,000 years B.P.

70b. The inextricable linkages between the water cycle and climate ensure that potential future climate change will significantly alter hydrologic processes throughout the world. All natural hydrologic processes--precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of groundwater, and evapotranspiration--will be affected if climate changes.

70c. As a result of changes in key hydrologic variables such as precipitation, evaporation, soil moisture, and runoff, climate change is expected to have significant effects on water availability. Early hydrologic impact studies provide evidence that relatively small changes in precipitation and evaporation patterns might result in significant, perhaps critical, changes in water availability. For many aspects of water resources, including human consumption, agricultural water supply, flooding and drought management, groundwater use and recharge, and reservoir design and operation, these hydrologic changes will have serious implications.

70d. Despite significant differences among climate change scenarios, a consistent finding among hydrologic impact studies is the prediction of a reduction in summer soil moisture and changes in the timing and magnitude of runoff. Winter runoff is expected to increase and summer runoff to decrease. These results appear to be robust across a range of climate change scenarios.

70e. Future directions for research and analyses suggest that improved estimates of climate variables are needed from large-scale climate models; innovative techniques are needed for regional assessments; increased numbers of assessments are necessary to broaden our knowledge of effects on different users; and increased analyses of the impacts of changes in water resources on the economy and society are necessary.

71. MORBIDITY AND MORTALITY RATES ARE ASSOCIATED WITH WEATHER EXTREMES IN OUR SOCIETY (chapter 16).

71a. Weather has a profound effect on human health and well being. It has been demonstrated that weather is associated with changes in birth rates, outbreaks of pneumonia, influenza, and bronchitis, and related to other morbidity effects, and is linked to pollen concentrations and high pollution levels.

71b. Large increases in mortality have occurred during previous heat and cold waves. It is estimated that 1,327 fatalities occurred in the United States as a result of the 1980 heat wave, and Missouri alone accounted for over 25 percent of that total.

71c. Hot weather extremes appear to have a more substantial impact on mortality than cold wave episodes.

71d. Threshold temperatures, which represent maximum and minimum temperatures associated with increases in total mortality, have been determined for various cities. These threshold temperatures vary regionally; for example, the threshold temperature for winter mortality in mild southern cities such as Atlanta is 0°C and for more northerly cities such as Philadelphia, threshold temperature is -5°C.

71e. If future global warming induced by increased concentrations of trace gases does occur, it has the potential to affect human mortality significantly. In one study, total summertime mortality in New York City was estimated to increase by over 3,200 deaths per year for a 7°F trace-gas-induced warming without acclimatization. If New Yorkers fully acclimatize, the number of additional deaths is estimated to be no different than today. It is hypothesized that if climate warming occurs, some additional deaths are likely to occur because economic conditions and the basic infrastructure of the city will prohibit full acclimatization even if behavior changes.

QUANTITATIVE ASSESSMENT OF RISKS WITH INTEGRATED MODEL

AN INTEGRATED ASSESSMENT OF RISKS FOR VARIOUS SCENARIOS OF OZONE-DEPLETING SUBSTANCES SHOWS THAT HARM DEPENDS ON THE LEVEL OF THE PRODUCTION OF CHLORINE AND BROMINE BEARING SUBSTANCES.

Risks are evaluated by using the integrated model to simulate the impact of "what-if" scenarios of production of ozone-depleting substances and scenarios of other trace gas concentrations on the atmosphere and on human health and the environment. Sensitivity analyses of alternative assumptions are also conducted.

Analysis of the results of all the scenarios indicates that adverse impacts on health and welfare are lowered with reductions in the production of ozone-depleting substances.

72. MODIFICATION OF THE TRACE GAS COMPOSITION OF THE ATMOSPHERE CAN BE EXPECTED TO ALTER COLUMN OZONE ABUNDANCE (chapter 18).

72a. The range of global average total column ozone change projected for the year 2075 based on a parameterized representation of a one-dimensional model could vary from as high as over 50 percent depletion, for a case where global use of chlorine and bromine bearing substances grows at an average annual rate of 2.8 percent from 1985 to 2100 (5.0 percent per year from 1985 to 2050, followed by no growth through 2100), to increased abundance of ozone of approximately 3 percent, for a case where global use of chlorine and bromine bearing substances declines to 20 percent of its 1985 value by 2010. Exhibit ES-6 displays the global ozone change estimates for these two scenarios, as well as estimates for four scenarios in between; the six "what if" scenarios examined include:

- 80% Reduction: Use of chlorine and bromine bearing substances declines to 20 percent of its 1985 value by 2010, and remains constant thereafter, yielding approximately 3.0 percent increased ozone abundance by 2075;
- No Growth: no growth in use of chlorine and bromine-bearing substances from 1985 to 2100, yielding approximately 0.3 percent increased ozone abundance by 2075;
- 1.2% Growth: 1.2 percent growth from 1985 to 2050, followed by no growth, yielding approximately 4.5 percent depletion by 2075;
- 2.5% Growth: 2.5 percent growth from 1985 to 2050, followed by no growth, yielding approximately 25 percent depletion by 2075;
- 3.8% Growth: 3.8 percent growth from 1985 to 2050, followed by no growth, yielding over 50 percent depletion by 2075;
- 5.0% Growth: 5.0 percent growth from 1985 to 2050, followed by no growth, yielding over 50 percent depletion by 2075.

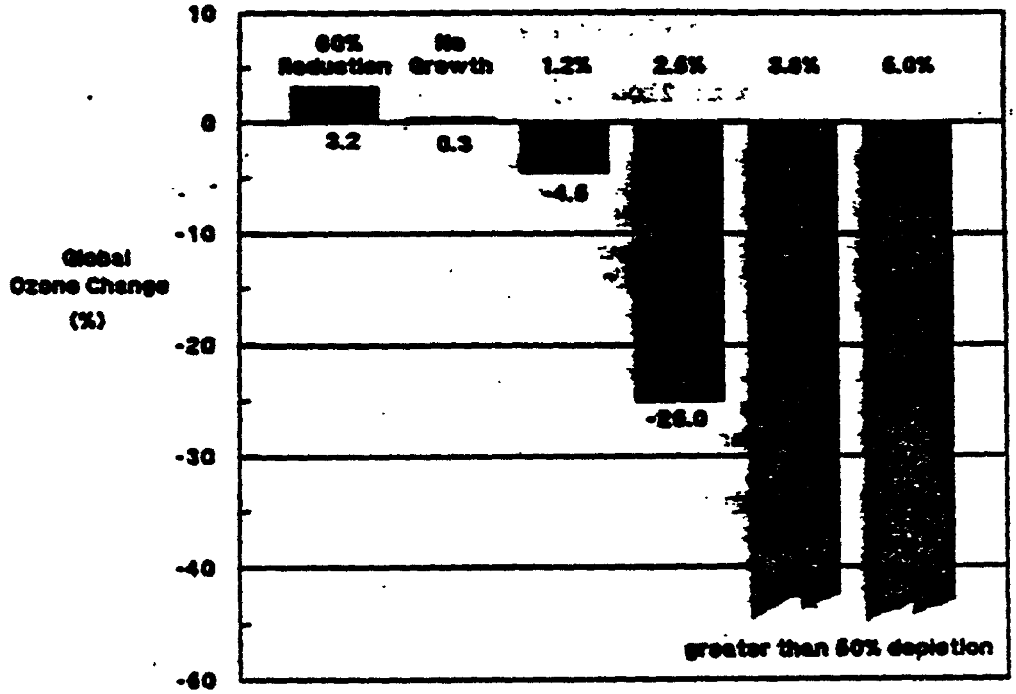
The trace gas concentration assumptions used in these six cases are: CO_2 -- NAS 50th percentile; CH_4 -- 0.017 ppm per year (approximately 1 percent of current CH_4 concentration); and N_2O -- 0.20 percent per year.

72b. Current data are not sufficient for distinguishing whether CH_4 concentrations are likely to increase in a linear manner (e.g. at 0.017 ppm per year, or approximately 1 percent of current concentrations) or in a compound manner (e.g., at 1 percent per year, compounded annually). The sensitivity of the ozone change estimates in 2075 was evaluated for the following six assumptions regarding future CH_4 concentrations:

- Scenario A: compound annual growth of 1 percent from 1985 to 2010, followed by constant concentrations at 2.23 ppm;

EXHIBIT ES-6

ESTIMATES OF GLOBAL OZONE DEPLETION IN 2075
FOR SIX CASES OF CFC USE



Using a parameterized representation of a one-dimensional model, the potential change in ozone was evaluated for six scenarios: 80% Reduction: global CFC use declines to 20 percent of current levels by 2010, and remains constant thereafter; No Growth: no growth in CFC use from current levels; 1.2% Growth: 1.2 percent growth from 1985 to 2050, followed by no growth; 2.5% Growth: 2.5 percent growth from 1985 to 2050, followed by no growth; 3.8% Growth 3.8 percent growth from 1985 to 2050, followed by no growth; 5.0% Growth: 5.0 percent growth from 1985 to 2050, followed by no growth through 2100). The trace gas concentration assumptions used in these six cases are: CO_2: NAS 50th percentile; CH_4: 0.017 ppm per year (approximately 1 percent of current CH_4 concentration); and N_2O: 0.20 percent per year.

Assumptions:

-- Current 1-D models accurately reflect global depletion; Antarctic ozone hole has no impact on global ozone levels.

-- Greenhouse gases that counter depletion grow at historically-extrapolated rates.

-- Growth rates for ozone depletion are for global emissions; it is assumed that emissions do not increase after 2050.

-- Ozone depletion limited to 50 percent.

- Scenario B: linear growth at 0.01275 ppm per year (75 percent of the 0.017 ppm growth);
- Scenario C: linear growth of 0.017 ppm per year (approximately 1 percent of current concentrations);
- Scenario D: linear growth at 0.02125 ppm per year (125 percent of the 0.017 ppm growth);
- Scenario E: compound annual growth of 1 percent;
- Scenario F: compound annual growth of 1 percent from 1985 to 2020, growing to 1.5 percent compound annual growth by 2050 and thereafter.

For the 2.5% Growth scenario, the estimate of ozone depletion by 2075 ranges from about 14 percent (Scenario F) to 30 percent (Scenario A) across these six CH_4 assumptions evaluated. Exhibit ES-7 displays the results for these six CH_4 assumptions. As shown in the exhibit, the difference between the 1 percent linear (0.017 ppm per year) and 1 percent compounded assumptions (Scenarios C and E) is approximately 6 percent depletion. This sensitivity of the ozone depletion estimates to the assumption about linear versus compound growth of CH_4 concentrations is much larger than the sensitivity to the range of assumptions examined regarding future CO_2 concentrations (from the 25th to the 75th percentile NAS estimates) and regarding future N_2O concentrations (from 0.15 percent annual compound growth to 0.25 percent annual compound growth).

73. TWO-DIMENSIONAL (2-D) MODELS PREDICT GREATER AVERAGE GLOBAL DEPLETION THAN ONE-DIMENSIONAL (1-D) MODELS. 2-D MODELS ALSO PREDICT THAT OZONE DEPLETION WILL EXCEED THE GLOBAL AVERAGE AT HIGH LATITUDES AND BE LESS THAN THE GLOBAL AVERAGE AT THE EQUATOR (chapter 18).

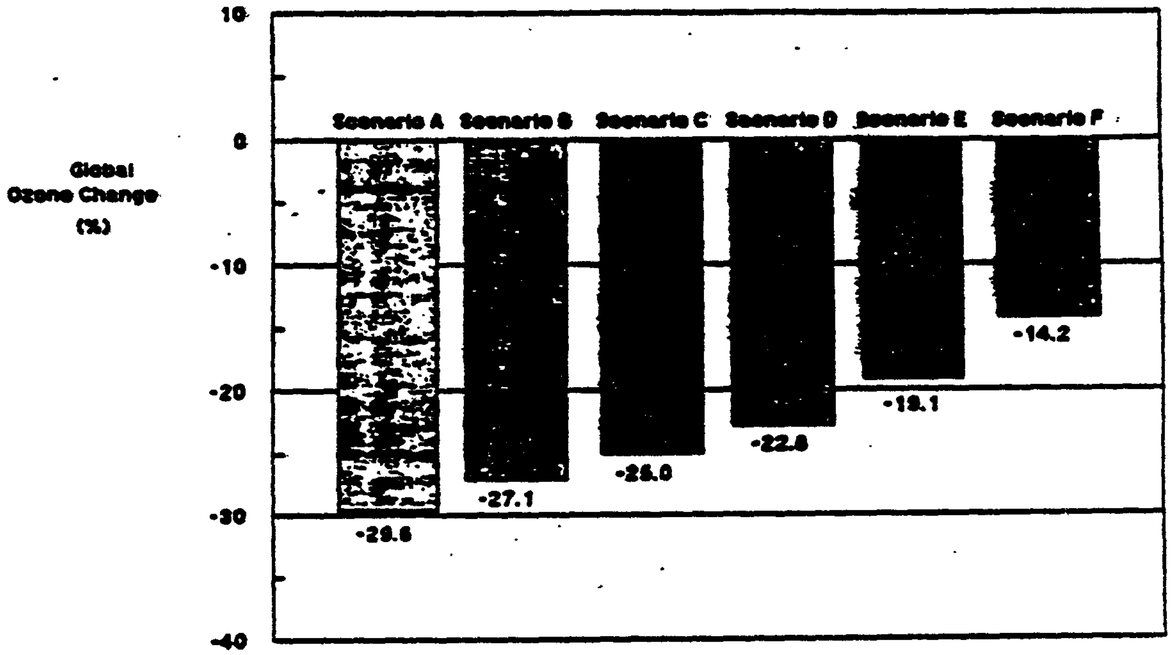
73a. For a case of 3 percent annual growth in emissions of CFCs, no emissions of Halons, and increases in trace gases of: CO_2 -- approximately 0.6 percent per year; CH_4 -- 1 percent per year; and N_2O -- 0.25 percent per year, a 2-D model estimates approximately 5.4 percent global average depletion by 2030. For the same scenario of emissions and trace gas concentrations, the parameterized representation of a 1-D model estimates only 3.0 percent depletion by 2030.

73b. For this same case of emissions and trace gas concentrations, the 2-D model estimates of ozone depletion in 2030 at high latitudes are approximately: 60°N -- 8.7 percent; and 50°N -- 7.0 percent.

74. ESTIMATES OF ATMOSPHERIC MODIFICATION, SKIN CANCER CASES AND DEATHS, CATARACT CASES, MATERIALS DAMAGE, GLOBAL TEMPERATURE, AND SEA LEVEL DEPEND ON THE RATE AT WHICH OZONE-DEPLETING GASES GROW, ATMOSPHERIC RESPONSE, DOSE RESPONSE, AND WHETHER GREENHOUSE GASES THAT COUNTER OZONE DEPLETION GROW INDEFINITELY. THE ASSUMPTIONS BEHIND QUANTITATIVE PROJECTIONS MUST BE NOTED CAREFULLY (chapter 18).

EXHIBIT ES-7

ESTIMATES OF GLOBAL OZONE DEPLETION IN 2075
FOR SIX METHANE CONCENTRATION ASSUMPTIONS



Using a parameterized representation of a one-dimensional model, the potential change in ozone was evaluated for six assumptions about future methane concentration: Scenario A: compound annual growth of 1 percent from 1985 to 2010, followed by constant concentrations at 2.23 ppm; Scenario B: linear growth at 0.01275 ppm per year (75 percent of the 0.017 ppm growth); Scenario C: linear growth of 0.017 ppm per year (approximately 1 percent of current concentrations); Scenario D: linear growth at 0.02125 ppm per year (125 percent of the 0.017 ppm growth); Scenario E: compound annual growth of 1 percent; and Scenario F: compound annual growth of 1 percent from 1985 to 2020, growing to 1.5 percent compound annual growth by 2050 and thereafter.

All estimates based on the 2.5% Growth scenario 1985 to 2100 (2.5 percent growth from 1985 to 2050, followed by no growth thereafter). The other trace gas assumptions used in these cases are: CO_2: NAS 50th percentile; and N_2O: 0.20 percent growth per year.

Assumptions:

-- Current 1-D models accurately reflect global depletion; Antarctic ozone hole has no impact on global ozone levels.

-- Greenhouse gases that counter depletion grow at historically-extrapolated rates.

-- Growth rates for ozone depletion are for global emissions; it is assumed that emissions do not increase after 2050.

-- Ozone depletion limited to 50 percent.

74a. The models used in this risk assessment assume that Antarctic ozone depletion has no global implications and that global trends do not invalidate estimates of current models.

74b. Except as noted, projected effects assume that: greenhouse gases grow at historical rates indefinitely; current one-dimensional models accurately project depletion; production of ozone depleters does not grow after 2050; ozone depletion is limited to 50 percent; the action spectrum causing skin cancers is DNA; and the temperature sensitivity of the earth to doubled CO_2 is 3°C.

74c. In 2100, projections of ozone depletion range from over 50 percent for the 5% Growth scenario (ozone depletion is constrained at 50 percent in this analysis) to 47 percent for the 2.5% Growth scenario to an increase in column ozone abundance of nearly 5 percent for the 80% Reduction scenario.

74d. For cohorts born before 2075, the number of additional nonmelanoma skin cancers projected ranges from a 261.5 million increase for the 5% Growth scenario to a 115 million increase for the 2.5% Growth scenario to a reduction of 6.5 million skin cancers for the scenario of 80% Reduction in all ozone depleters.

74e. For cohorts born before 2075, the increase in total melanoma cases ranges from a 1.3 million case increase for the 5% Growth scenario to a 609,000 increase for the 2.5% Growth scenario to 54,000 fewer cases for the scenario of an 80% Reduction in all ozone depleters.

74f. For cohorts born before 2075, total mortality from melanoma and nonmelanoma ranges from a 5.6 million increase for the 5% Growth scenario to a 2.4 million increase for the 2.5% Growth scenario to 115,000 fewer cases for the scenario of 80% Reduction in all ozone depleters.

74g. For cohorts born before 2075, the increase in total cataract cases ranges from 26 million for the 5% Growth scenario to 15.1 million for the 2.5% Growth scenario to 9,500 for the scenario of 80% Reduction in ozone depleters.

74h. The rise in global temperature by 2075 ranges from 11.6°C in the 5% Growth scenario to 5.6°C in the 2.5% Growth scenario to 4°C in the scenario of 80% Reduction in all ozone depleters.

74i. Impacts are also projected for other areas such as sea level rise, ground-based ozone, materials, aquatics, and soybean yield.

75. <u>QUANTITATIVE ESTIMATES OF RISKS VARY WITH ASSUMPTIONS ABOUT FUTURE EMISSIONS OF GREENHOUSE GASES THAT WILL CONTRIBUTE TO GLOBAL WARMING</u> (chapter 18).

75a. Model projections that extrapolate historical growth rates of greenhouse gases, which tend to counter ozone depletion, into the indefinite future assume certain policy decisions from future decisionmakers; alternative assumptions are possible.

75b. If future decisionmakers limit the concentrations of CO_2, N_2O, and CH_4 to prevent global warming from exceeding 2°C (±50%) in 2075, they would by necessity have to limit growth of ozone depleters to the No Growth case; for other cases increases in ozone depleters would be too large to achieve that objective.

75c. Ozone depletion associated with the No Growth or 1.2% Growth scenarios increases nearly 3 to 5 percent if global warming is limited to 3°C (±50%); skin cancer deaths would increase 43 percent for people alive today.

75d. Estimates of methane emissions are inherently uncertain even without consideration of future policy decisions and could affect quantitative risk estimates.

76. <u>QUANTITATIVE ESTIMATES OF RISK VARY WITH UNCERTAINTY ABOUT DOSE-RESPONSE COEFFICIENTS, ACTION SPECTRUM, LIMITS OF OZONE DEPLETION, AND RESPONSIVENESS OF MODELS TO ATMOSPHERIC DEPLETION</u> (chapter 18).

76a. For people alive today and born before 2075, additional skin cancer cases would be reduced 45 percent if one assumes the lower dose-response coefficients that are one standard error below the best estimate and 66 percent higher if one assumes the higher coefficients that are one standard error above the best estimate.

76b. For people alive today and born before 2075, additional skin cancer cases would be reduced 11 percent if the Erythema action spectrum, rather than the DNA action spectrum, were used to measure health effects.

76c. Limiting projected depletion to 50 percent from what the parameterized 1-D model would project reduces projected deaths for later cohorts. For people born from 2030 to 2074, limiting depletion to 50 percent reduces deaths by 13 percent for the 2.5% Growth scenario and 66 percent for the 5% Growth scenario.

76d. For people alive today and born before 2075, skin cancer cases would be reduced 62 percent in the 2.5% Growth scenario if the atmosphere were less sensitive to potential ozone depleters (using the 10th percentile), and increased 54 percent if the atmosphere were more sensitive (using the 90th percentile).

77. <u>WHILE NATIONAL QUANTITATIVE ESTIMATES OF AQUATIC, CROP, GROUND-BASED OZONE, AND SEA LEVEL RISE DAMAGE CANNOT BE MADE AT THIS TIME, CASE STUDY RESULTS INDICATE THAT SIGNIFICANT INCREASES IN GROUND-BASED OZONE, LOSS OF AQUATIC LIFE, SEA LEVEL RISE DAMAGE, AND LOSS OF CROP YIELD ARE POSSIBLE</u> (chapter 18).

MAJOR PRIOR ASSESSMENTS OF THIS ISSUE

A number of prior assessments of stratospheric modification and climate change have been done. A partial list with descriptions is included below:

STRATOSPHERIC OZONE

1. National Academy of Sciences (NAS), 1975, 1976, 1979, 1982, 1983

Several assessments of anthropogenic influences on the stratospheric ozone layer were coordinated by the National Academy of Sciences. The first report, in 1975, focused on the effects of proposed fleets of supersonic transports on the stratosphere. Subsequent reports focused on chlorofluorocarbons.

2. National Aeronautics and Space Administration (NASA), 1977, 1986

NASA has convened several technical panels to review models and chemistry. In addition, it completed a scientific assessment in 1986.

3. World Meteorological Organization,
National Aeronautics and Space Administration,
Federal Aviation Administration,
National Oceanic and Atmospheric Administration,
United Nations Environment Programme,
Commission of the European Communities, and
Bundeministerium fur Forschung und Technologie

International assessments of the stratosphere have been conducted by the European Community, the United Kingdom's Department of the Environment (1979), and by the United Nations Environment Coordinating Committee on the Ozone Layer (1981, 1984, 1986).

The most recent and most ambitious assessment of the scientific issues regarding the stratosphere was coordinated by the World Meteorological Organization with the assistance of several other organizations. Approximately 150 of the world's leading scientists participated in this assessment.

CLIMATE

1. Climatic Impact Assessment Program, 1974

Initial concern over anthropogenic influences on the climate and the stratospheric ozone layer led in 1971 to the establishment of the Climatic Impact Assessment Program (CIAP). Coordinated by the Department of Transportation, CIAP's objective was to assess, by a report in 1974, the impacts of climatic changes due to projected fleets of supersonic transports.

2. National Academy of Sciences: 1979, 1982, 1983

Three panels were convened by the National Academy of Sciences to assess the scientific basis and certainty of the effects of carbon dioxide concentrations on global climate. Reports were released in 1979, 1982, and 1983.

3. World Meteorological Organization,
International Council of Scientific Unions, and
United Nations Environment Programme

Efforts to achieve an international scientific consensus on carbon dioxide, trace gases, and climate were coordinated by the World Meteorological Organization (WMO), International Council of Scientific Unions (ICSU), and United Nations Environment Programme (UNEP). Assessments were released in 1979, 1981, and 1985.

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