# THE SKY IS THE LIMIT:
## Strategies for Protecting the Ozone Layer

Alan S. Miller
Irving M. Mintzer



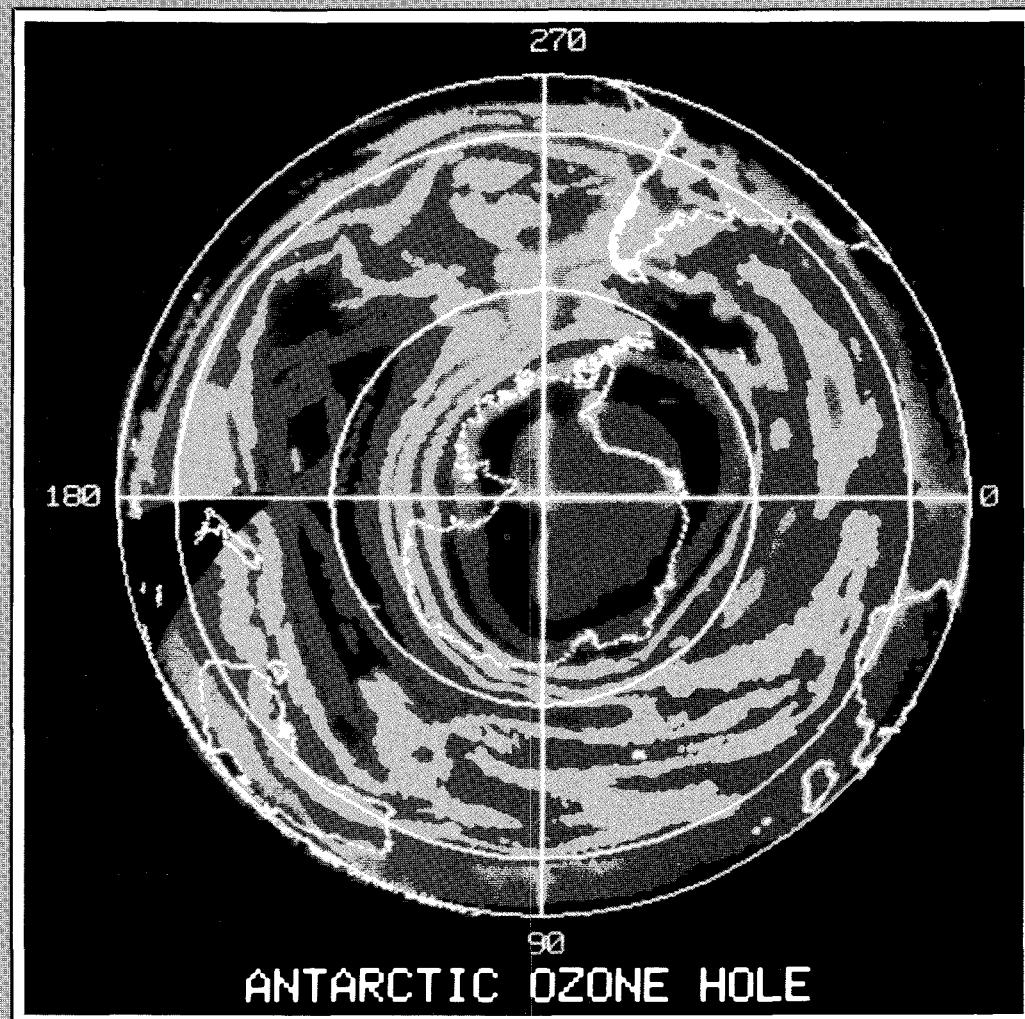ANTARCTIC OZONE HOLE
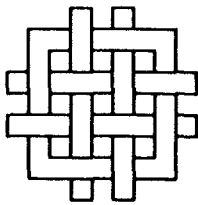
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# Acknowledgments

# Foreword

Seldom has an issue been so dramatically transformed in its content, urgency, and policy dimensions in so short a time as the fate of the stratospheric ozone layer was in 1985–86.

The role of chlorofluorocarbons (CFCs) in destroying the ozone layer that shields the earth from incoming ultraviolet radiation has been modeled and debated since the reaction was first hypothesized by Molina and Rowland in 1974. The urgency of the issue has fluctuated widely with scientific estimates of the rate of ozone depletion and the tides of new hypotheses, assumptions, and models. One cannot say for certain that five years hence we will not look back on this period as just one more temporary peak of concern. However, several events of the past 18 months suggest that the issue has been profoundly and permanently transformed.

Among these events was the signing of the Vienna Convention for the Protection of the Ozone Layer, establishing for the first time the framework for a cooperative global pollution-control agreement, and moreover one that attempts to anticipate and avert, rather than clean up, a problem. In both regards, the Vienna Convention established an international precedent. If the negotiations of the coming year are able to add regulatory teeth to this framework, the Convention will also have broken through an important psychological barrier—what people see as the limits of international cooperation.

In 1985 came the stunning announcement of the discovery of a "hole" in the ozone layer, a hole the size of the continental United States. Although its causes and impacts are not yet understood, the Antarctic hole has already dramatically altered the policy landscape by underscoring the potential for large unanticipated atmospheric changes, the possibility of sudden threshold effects rather than smooth incremental change, and the size of the stakes in the unplanned global experiment on which mankind is embarked.

Also during this period, the expected rate of the greenhouse warming accelerated as the role played by the so-called non-$CO_2$ greenhouse gases—among them,

CFCs and tropospheric ozone—became clearer to scientists. With a warming equivalent to what a doubled $CO_2$ level would cause now expected as soon as the 2030s, the greenhouse question shifted from the arena of pure research to that of policy analysis: from questions of what would happen and why to questions of what should be done. Scientists meanwhile added a new dimension to an already complex problem by insisting that because of the many connections between them—chemical overlaps and feedback loops—climate change and stratospheric ozone depletion must be understood and addressed as a single, integrated phenomenon.

The fall of 1986 saw the fourth of these major milestones. This was the endorsement by U.S. and European users and producers of CFCs, and separately by DuPont, the largest single CFC manufacturer, of limits on CFC production. The shift in industry's position, especially its recognition that action should be taken despite large remaining scientific uncertainties, marked a major step forward.

The fate of the ozone layer is far from settled, however. How CFC emissions might be curbed, how such actions might be internationally enforced, how the burden should be shared among developed and developing countries, what level of restriction current scientific certainty justifies, and what types of regulation would minimize economic costs and induce the innovation that will bring safer substitutes all remain unanswered questions.

These questions are the subject of this particularly timely report, which analyzes the various possibilities—technical and institutional—of the now-transformed policy picture. Based on their analysis of the latest discoveries and developments, the authors propose a bold but soundly based regulatory plan that might provide the foundation for a successful global response to the atmospheric challenge before us.

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World Resources Institute

# Introduction

Governments around the world will soon decide whether to adopt policies that could determine the fate of the ozone layer—the earth's shield from harmful ultra-violet radiation. The Vienna Convention for the Protection of the Ozone Layer, signed on March 22, 1985, created a framework for scientific cooperation and initiated a two-year program of workshops and information exchange that will form the basis for a protocol on the control of substances thought to threaten the ozone layer.[1] As of mid-1986, 28 countries had signed the Convention, including the major producers and users of chlorofluorocarbons (CFCs), the most important of the suspect chemicals. The United States Senate ratified the Convention in July 1986.

The United States is also reviewing the need for further domestic regulatory action. The Clean Air Act requires controls on any substances that the Environmental Protection Agency (EPA) determines "may reasonably be anticipated to affect the stratosphere, and to . . . endanger public health or welfare."[2] After being sued by an environmental group, the Natural Resources Defense Council, EPA announced its intent to determine the need for and form of any U.S. regulation by November 1987—a date chosen to parallel the Convention process and put domestic action in line with international negotiations.[3]

Recent scientific developments have increased the urgency of governmental deliberations. In 1985, British scientists reported finding losses of ozone in the Antarctic in spring that are far greater than current atmospheric models can explain.[4] National Aeronautics and Space Administration (NASA) satellite measurements have confirmed these ozone measurements, the lowest ever recorded over the earth.

In June 1986, EPA and the United Nations Environment Programme (UNEP) jointly sponsored a week-long conference on ozone depletion and climate change, highlighting the wide-ranging risks that such changes pose to human health and the environment.[5] Summarizing the status of atmospheric science, a 1986 report by NASA to Congress concluded that "society is conducting a giant experiment on a global scale by increasing the concentrations of trace gases without knowing the environmental consequences."[6]

Governmental decisions concerning ozone depletion will also greatly influence the "greenhouse" problem, the expected warming of the earth as heat-trapping gases build-up in the atmosphere. CFCs contribute to the greenhouse effect, as would the changes predicted in the distribution of ozone. Apart from this direct impact on the rate of greenhouse warming, the Convention could serve as a model for future efforts to work out an international strategy to control greenhouse gases.

This report reviews scientists' current understanding of the risks of ozone modification, describes techniques for reducing or eliminating emissions of CFCs, and then addresses several key policy issues before the United States and other nations: the seriousness of the ozone depletion problem, allowing for possible growth in gases with offsetting effects; the appropriate timing of any governmental action, given that widely recognized models show no net change in global ozone from current CFC emission levels for twenty years or more; and the most effective and workable form for domestic and international governmental action. Finally, specific government actions, both national and international, are proposed.

# I. The Science of the Ozone Layer

Small quantities of ozone ($O_3$) in the atmosphere are critical to the balance that allows life on earth. The concentration of ozone varies with altitude. Most ozone is in the stratosphere 6 to 30 miles above the earth, though smaller amounts are associated with pollution problems closer to the surface. *(See Figure 1.)* Ozone absorbs much of the ultraviolet radiation that the sun emits in wave-lengths harmful to humans, animals, and plants (240-329 nm—a spectrum of wavelengths referred to as "UV-B"). Ozone concentrations at different altitudes also affect temperature, air movements, and the downward emission of infrared radiation, which in turn influence the radiative and meteorological processes that determine climate.[7] Thus, if the amount or the vertical distribution of ozone changes significantly, major environmental consequences could result—among them, climate change from a greenhouse warming.

Ozone is formed in the stratosphere when ultraviolet radiation (UV) breaks down diatomic molecules of oxygen ($O_2$). Once split, the two oxygen atoms combine with two molecules of diatomic oxygen to form molecules of ozone ($O_3$). Ozone molecules are in turn broken apart by UV, forming $O_2$ and O. This reversible process balances O, $O_2$, and $O_3$ in the stratosphere. But reactions between ozone molecules and oxides of chlorine, nitrogen, bromine and other elements can upset this chemical balance and reduce the amount of $O_3$. Acting as catalysts, single reactive molecules of chlorine or nitrogen can destroy thousands of ozone molecules. *(See Figure 2, and Appendix 1.)*

In 1974, Drs. Mario Molina and F. Sherwood Rowland hypothesized that the growing use of a family of chemical compounds known as chlorofluorocarbons (CFCs) could be particularly worrisome.[8] *(See Box.)* CFCs are very non-reactive chemicals, which makes them safe and useful for many applications—aerosol sprays, refrigeration, foam blowing, solvents and more. Whereas the lifetime of most chemicals in the atmosphere can be measured in weeks or months, the effect of CFCs can last for a century or more. But their unusual chemical stability allows them to reach the stratosphere. Fifteen to fifty kilometers above the
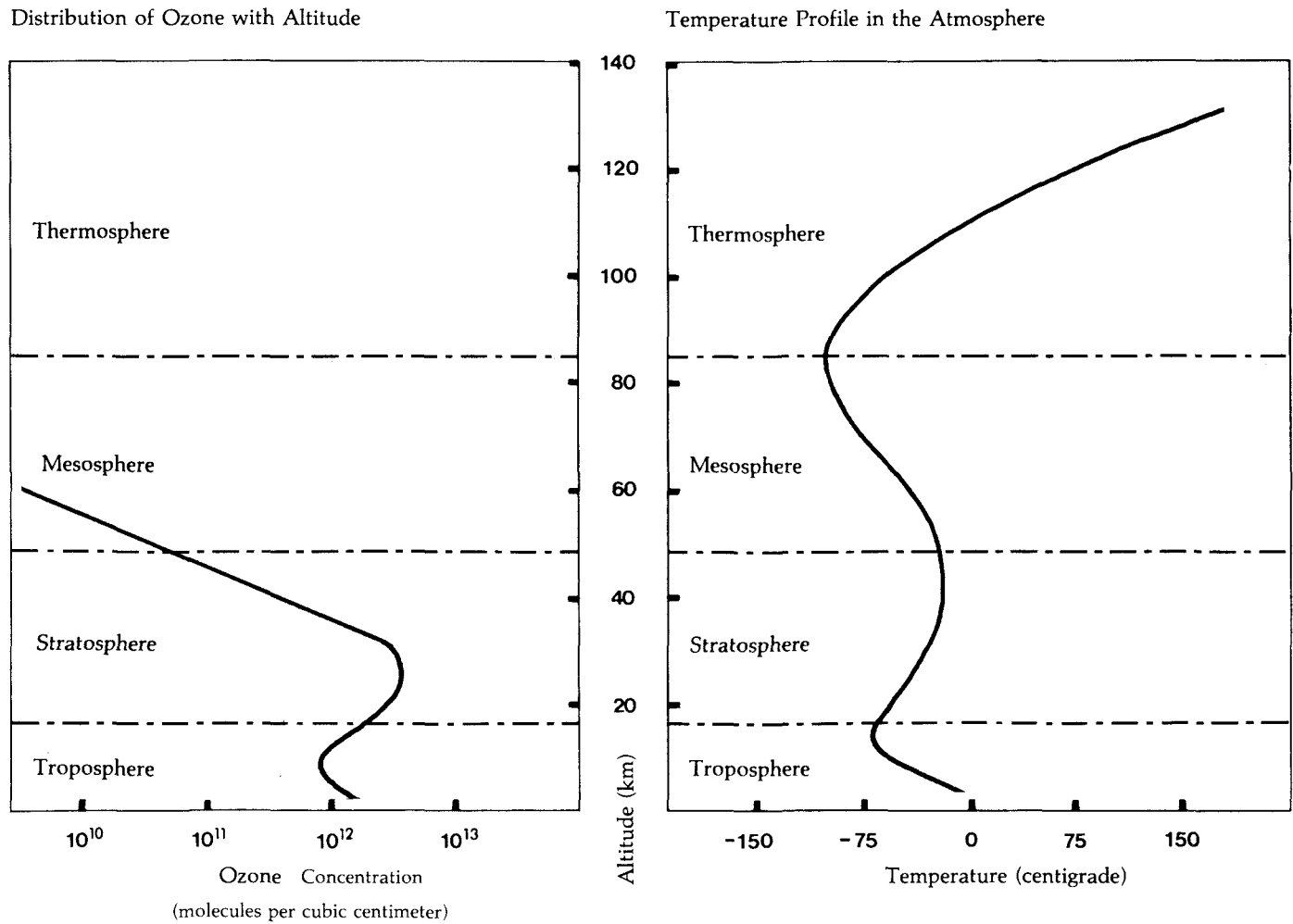
earth's surface, the intense ultraviolet radiation causes them to break apart releasing chlorine (a process known as photolysis). The chlorine then reacts with oxygen, nitrogen, and hydrogen oxides. The net result is a reduction in the concentration of ozone, while the chlorine remains.

Several other manmade chemicals—including methyl chloroform ($CH_3CCl_3$) and carbon tetrachloride ($CCl_4$)—besides CFCs may also threaten the ozone layer. Most exist in minute quantities, serve as intermediate products in the formation of other chemicals, or break down much faster in the atmosphere than the major CFCs, thus posing less of a threat. One exception may be the halons, chemicals used in fire extinguishers. Current production of these chemicals is relatively small, but they contain bromine (which may be a more effective ozone depleter than chlorine), their use is growing rapidly, and their atmospheric lifetimes may be as long as the CFCs. *(See Figures 3 a-b.)* Another potential source of depletion is $N_2O$, a source of concern should large numbers of supersonic aircraft ever become commercial.

Whether, when, and even where depletion occurs depends on numerous assumptions about the relative growth rates of different chemicals and the sensitivities of the model used to simulate what happens when the atmospheric chemistry is changed. Although basic concepts of stratospheric photochemistry have changed little for a decade, the description of the ozone "picture" has been refined.[9] Some chemicals released by mankind's activities, particularly carbon dioxide ($CO_2$) and methane ($CH_4$), increase ozone, potentially offsetting the depletion effect of CFCs. Tropospheric emissions of NO from subsonic aircraft and fossil fuel combustion may also increase ozone. The faster CFC emissions increase, the faster ozone depletion is expected to occur, while the effect of these other chemicals is in the opposite direction *(See Figure 4.)* The 1986 NASA report presented a range of estimates reflecting different potential growth rates for these chemicals. *(See Figure 5.)*

The possible interaction between chlorine and stratospheric odd-nitrogen ($NO_y$) creates another source of complexity. Some models show significant

**Figure 1.** Temperature Profile and Distribution of Ozone in the Atmosphere



Distribution of Ozone with Altitude

Temperature Profile in the Atmosphere

Thermosphere

Mesosphere

Stratosphere

Troposphere

140

120

100

80

60

40

20

Altitude (km)

$10^{10}$　　$10^{11}$　　$10^{12}$　　$10^{13}$

Ozone　Concentration

(molecules per cubic centimeter)

Thermosphere

Mesosphere

Stratosphere

Troposphere

-150　　-75　　0　　75　　150

Temperature (centigrade)

4

**Figure 2.** Selected Physical and Chemical Processes Impacting on Ozone Concentrations and Climatic Processes



Solar Radiation

STRATOPAUSE (50 km)

Photolysis of $O_2$
Production of $O_3$
|
Ozone concentrations
|
Slow transport of $O_3$

Photodissociation of CFCs → Cl, ClO

Dissociation of $N_2O$, NO, $NO_2$

CATALYTIC DESTRUCTION

Absorption of UV radiation
240nm — 290nm
290nm — 320nm (partial)

$O_3$

STRATOSPHERE

Stratospheric cooling

25 km

slow transport
CFCs, $N_2O$, $CO_2$, and others.

slow transport
Cl, ClO, NO, etc.

TROPOPAUSE (10-15 km)

CFC
$CO_2$
Trace gases

CFC
$CO_2$
Removal

$CH_4$ methane

Photochemical
$O_3$ smog

Tropospheric warming due to Greenhouse-effect absorption of long-wave radiation

CFC emissions   TROPOSPHERE

$CO_2$
$NO_x$
emissions

Major Ozone Modifying Substances Released by Human Activities

| Chemical | Source |
|---|---|
| CFC-11 ($CFCl_3$) }<br>CFC-12 ($CF_2Cl_2$) } | Used in aerosol propellants, refrigeration, foam blowing, and solvents |
| CFC-22 ($CHClF_2$) | Refrigeration |
| CFC-113 ($C_2Cl_3F_3$) | Solvents |
| Methyl Chloroform ($CH_3CCl_3$) | Solvent |
| Carbon Tetrachloride ($CCl_4$) | CFC production and grain fumigation |
| Halon 1301 ($CB_rF_3$) }<br>Halon 1211 ($CF_2ClB_r$) } | Fire extinguishant |
| Nitrous Oxides ($NO_x$) | By-product of industrial activity |
| Carbon Dioxides ($CO_2$) | By-product of fossil fuel combustion |
| Methane ($CH_4$) | By-product of agricultural, industrial, and mining activities |

**Figure 3a.** Ozone Depleting Potential Per Molecule
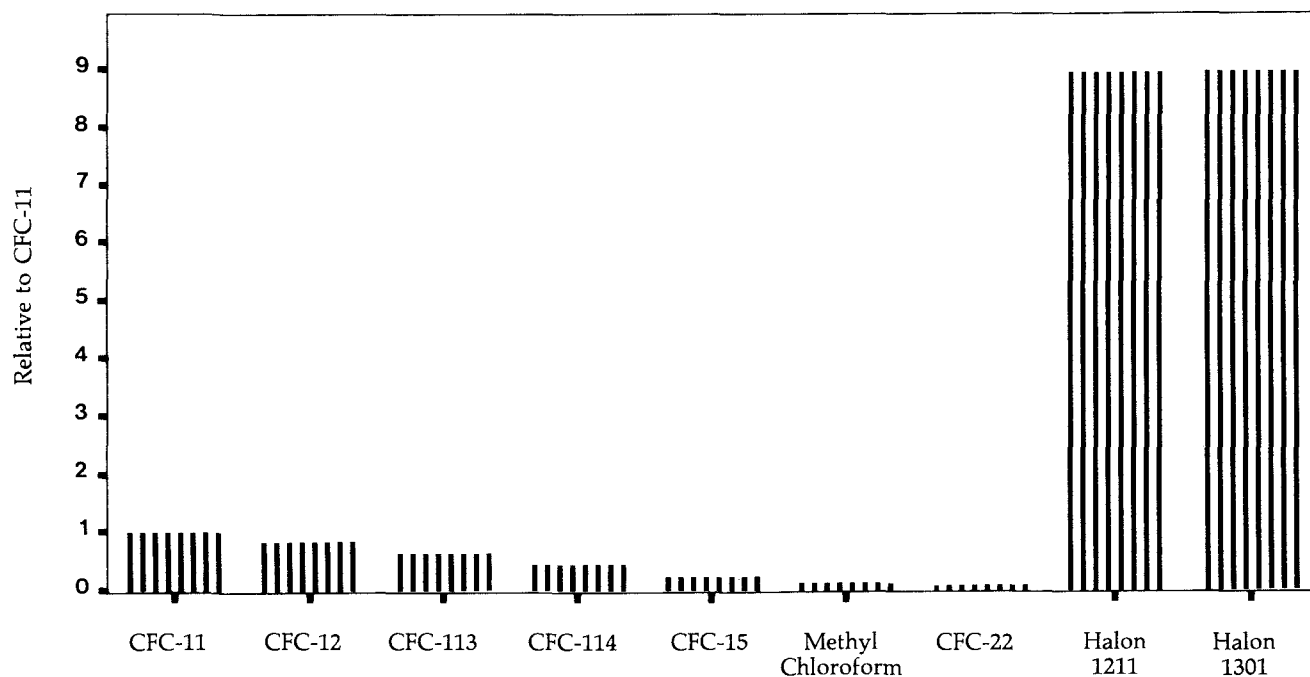
**Figure 3b.** Estimate of Ozone Depleting Potential
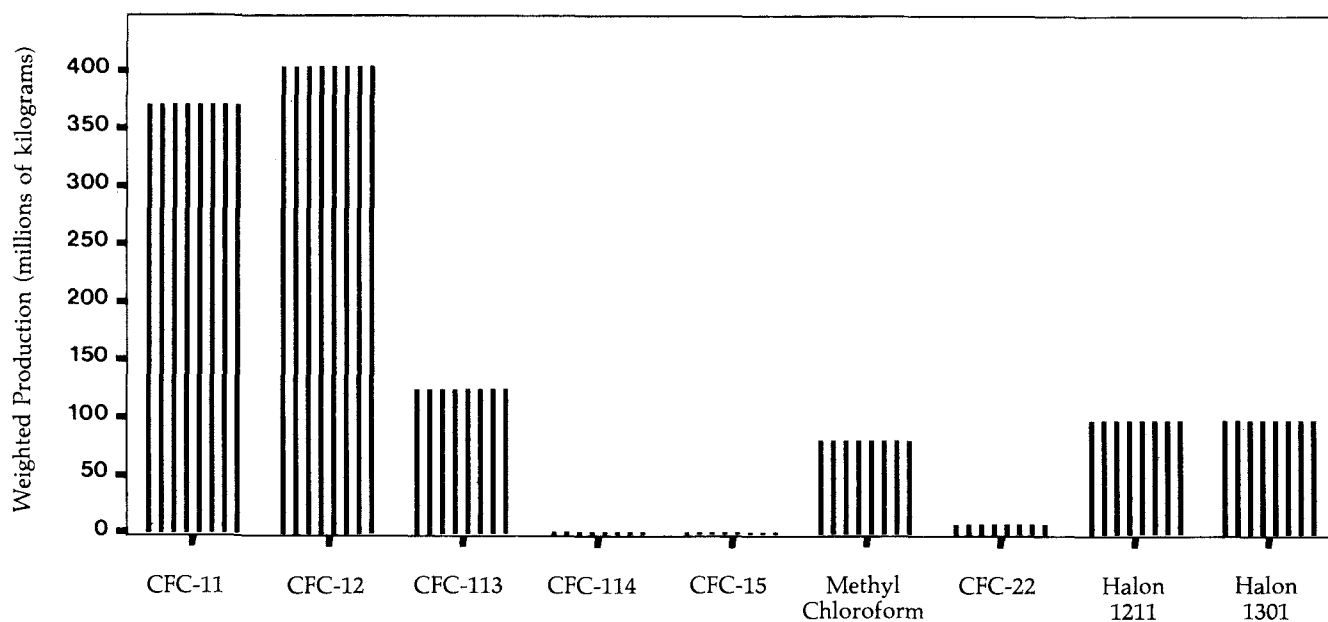
## What Are CFCs?

Although CFCs are usually referred to collectively, several different formulations are produced commercially and others have been developed experimentally. The major CFCs are:

CFC 11—$CCl_3F$—Trichlorofluoromethane
CFC 12—$CCl_2F_2$—Dichlorodifluoromethane
CFC 22—$CHClF_2$—Chlorodifluoromethane
CFC 113—$C_2Cl_3F_3$—Trichlorotrifluoromethane

The numbering system is based on a system originally devised by the DuPont Company and subsequently adopted worldwide to distinguish fluorinated hydrocarbons. The formulations listed above are denominated as follows:

The first digit on the right is the number of fluorine (F) atoms in the compound. The second digit from the right is the number of hydrogen (H) atoms plus one. The third digit from the right is the number of carbon (C) atoms minus one; if zero, this number is omitted.

How CFCs are formulated determines how much risk they pose to the ozone layer. CFC 11 and CFC 12 have expected atmospheric lifetimes of 75 and 110 years, so they are very threatening to the stratosphere. Formulations with hydrogen, such as CFC 22, degrade more rapidly than hydrogen-free formulations due to tropospheric reactions with hydroxyl "radicals" (OH). Similarly, formulations containing fluorine but not chlorine, such as $C_2H_4F_2$ (CFC 152a), do not threaten the stratosphere. *(See Section II. 3)*

**Figure 4.** Estimated Ozone Depletion for Different Rates of CFC Growth
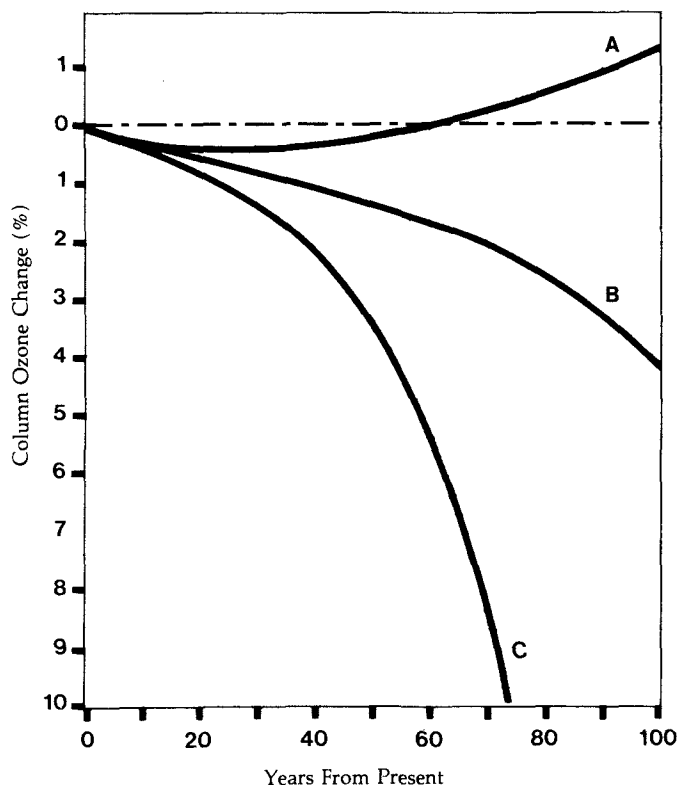


Calculated changes in total atmospheric ozone with time for time-dependent scenarios using the LLNL 1-D model with temperature feedback. Scenarios: A (CFC flux continues at 1980 level, $CH_4$ increased 1% per year, $N_2O$ increases 0.25% per year, and $CO_2$ increases 0.5% per year); B (CFC emissions begin at 1980 rates and increase at 1.5% per year, other trace gases change as with A.); C (same as B except CFC emissions increase at 3% per year).

**Source:** NASA, *Present State of Knowledge of the Upper Atmosphere* (1986)

**Figure 5.** Range of Change in Total Ozone Estimated by Five Representative Models for Illustrative Scenarios
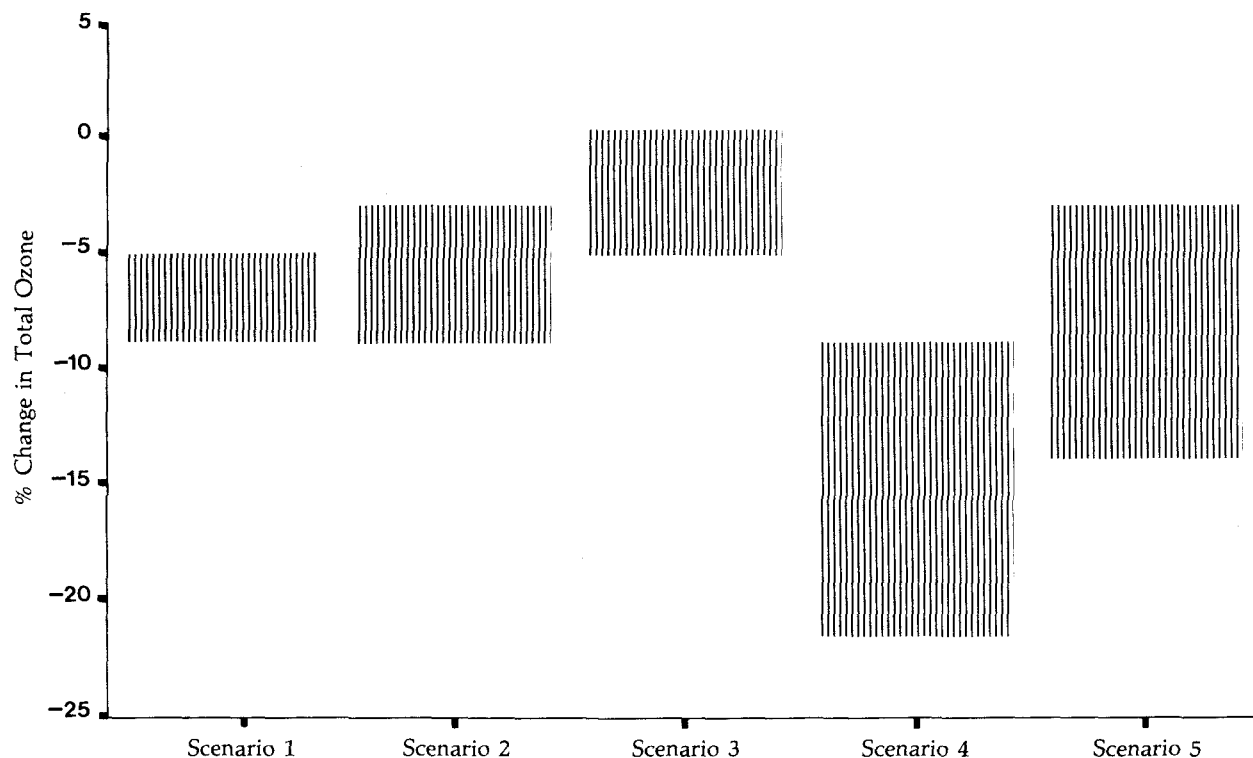


Scenario 1: CFC concentrations in equilibrium at 1980 levels

Scenario 2: Atmospheric chlorine concentration 8 ppbv

Scenario 3: Chlorine concentration 8 ppbv, methane concentration 2x current levels, nitrous oxide 1.2x current levels, carbon dioxide 2x current levels

Scenario 4: Atmospheric chlorine concentration 15 ppbv

Scenario 5: Atmospheric chlorine concentration 15 ppbv, other gases as in Scenario 3

Models used are from LLNL (Wuebbles), Harvard (Prather), AER (Sze), DuPont (Owens), IAS (Brasseur), and MPIC (Bruehl)

Further assumes background concentration of chlorine is 1.3 ppbv, no CFC in background

non-linearity in ozone depletion when the concentration of chlorine exceeds that of $NO_y$.[10] However, this would occur only if CFC emissions increased substantially.

Even if emissions of $CO_2$, $CH_4$, and $NO_x$ (oxides of nitrogen) increase ozone, offsetting the depletion caused by CFCs, the atmosphere may be radically altered because the effects occur at different altitudes. Modellers who assume stable emissions of CFCs but a continuation of recent growth rates for these other ozone perturbants find little net change in total ozone, but a significant change in its distribution by altitude. Such models predict that trace gases will reduce ozone

at heights above 30 km by up to 50 percent, though this reduction will be partially offset by an ozone increase in the lower stratosphere.[11] *(See Figure 6.)* This dynamic involves several different processes. Methane increases tropospheric ozone by chemical reactions, while the absorption of infrared radiation by methane and carbon dioxide cools the lower stratosphere, slowing reactions that destroy ozone. Another contributing factor is the "self-healing" effect—the accelerated production of ozone from molecular oxygen ($O_2$) in the lower stratosphere due to the increased ultra-violet rays that pass through the depleted upper and middle stratosphere. Changes in the *distribution* of ozone may

be an environmental concern even if the total *amount* of ozone doesn't change. Increasing CFCs and ozone—both greenhouse gases—in the lower stratosphere could contribute significantly to global warming and climate change. *(See pages 22–23.)*

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*Changes in the **distribution** of ozone may be an environmental concern even if the total **amount** of ozone doesn't change.*

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Depletion is further expected to vary significantly with latitude. *(See Figure 7.)* Between two and four times as much depletion occurs at the poles as at the equator primarily because the self-healing effect plays a much smaller role as incoming ultraviolet radiation diminishes with latitude.[12] From about 40 degrees latitude to the poles, there is no self-healing effect and ozone depletion is expected at all altitudes. Also, ozone concentrations vary seasonally, with greater depletion expected in winter when the solar effect is reduced.

The accuracy of modelling results can be empirically measured. Satellite and balloon measurements of the accumulation of trace gases show that most of the stratosphere's key constituents are as scarce or plentiful in a given area as models predict. However, important discrepancies in several measurements do limit confidence in the models.[13] For example, atmospheric measurements of two key chemicals, $HO_2$ (an oxide of hydrogen) and $ClO$ (an oxide of chlorine), differ substantially from theoretical predictions. Such discrepancies may reflect flaws in models or errors in very sensitive and difficult measurements.

Confidence in models would also increase if photochemically coupled chemicals in the same air mass could be measured simultaneously. Some satellite measurements have shown a world-wide reduction in ozone.[14] But how consistent are scientific instruments over time? Until researchers know, they can't say for certain that a global reduction in ozone has occurred.

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The uncertainty associated with current models and measurements still leaves the possibility of large future changes in depletion estimates.[15] Statistical analysis suggests that the uncertainties have been reduced to a factor of four or less—still very large but substantially reduced—and that the risk of depletion beyond that predicted is greater than the likelihood of depletion significantly less than that predicted. The major source of uncertainty may soon become the ambiguities associated with future rates of growth in trace gases—the one variable within mankind's control.[16]

Even when unequivocally established, ozone depletion cannot be readily ascribed to human activities. This uncertainty was highlighted by the 1985 discovery of the springtime Antarctic ozone "hole" which was not predicted and cannot yet be explained by models.[17] Several explanatory theories have been proposed (with varying emphasis on natural and anthropogenic causes), but a full understanding of this phenomenon and its global implications awaits further research.[18] Meantime, the rapidity of this unexpected depletion is cause for concern about the phenomenon itself and the potential for other unexpected large-scale changes, so the National Science Foundation has launched a major program of field measurements.[19] Data from other ground stations have revealed signs of other smaller areas of diminished ozone, notably an ozone loss of about 3 percent above Arosa, Switzerland.[20]

## Effects of Ozone Perturbations

Few of the possible consequences of ozone modification have been studied thoroughly, but what is known provides ample grounds for concern.[21] For example, the effect of natural incremental fluctuations of ozone levels by latitude and season is not always easily determined. There is no apparent threshold of acceptable ozone modification, though crop damage and other significant effects have been clearly identified with high levels of depletion.

The most clearly established human health effect of ozone depletion is an increase in the incidence of skin cancer in white-skinned populations. *(See Table 1.)* Scientists estimate that for every 1 percent increase in UV-B flux, the incidence of non-melanoma skin cancer will increase as much as 5 percent.[22] Most of these patches of cancer can be removed without adverse effect, but sunlight has also been implicated in malignant melanoma, a rarer but frequently fatal skin cancer that is increasing rapidly in the United States, Europe, and Australia.[23] According to a recent analysis, a 1-percent increase in UV-B would increase malignant melanoma mortality in the U.S. by 0.8 to 1.5 percent.[24] EPA estimates that constant CFC growth of 2.5 percent per year could cause an additional million skin cancers and 20,000 deaths over the lifetime of the existing U.S. population.[25] Recently, scientists have shown that sunlight suppresses the immune system, allowing tumors to grow.[26] A recent EPA survey report concluded that this effect may increase the incidence of Herpes virus infections and parasitic infections of the

**Figure 6.** Predicted Changes in Ozone by Altitude Over Time for One Scenario of Trace Gas Increase
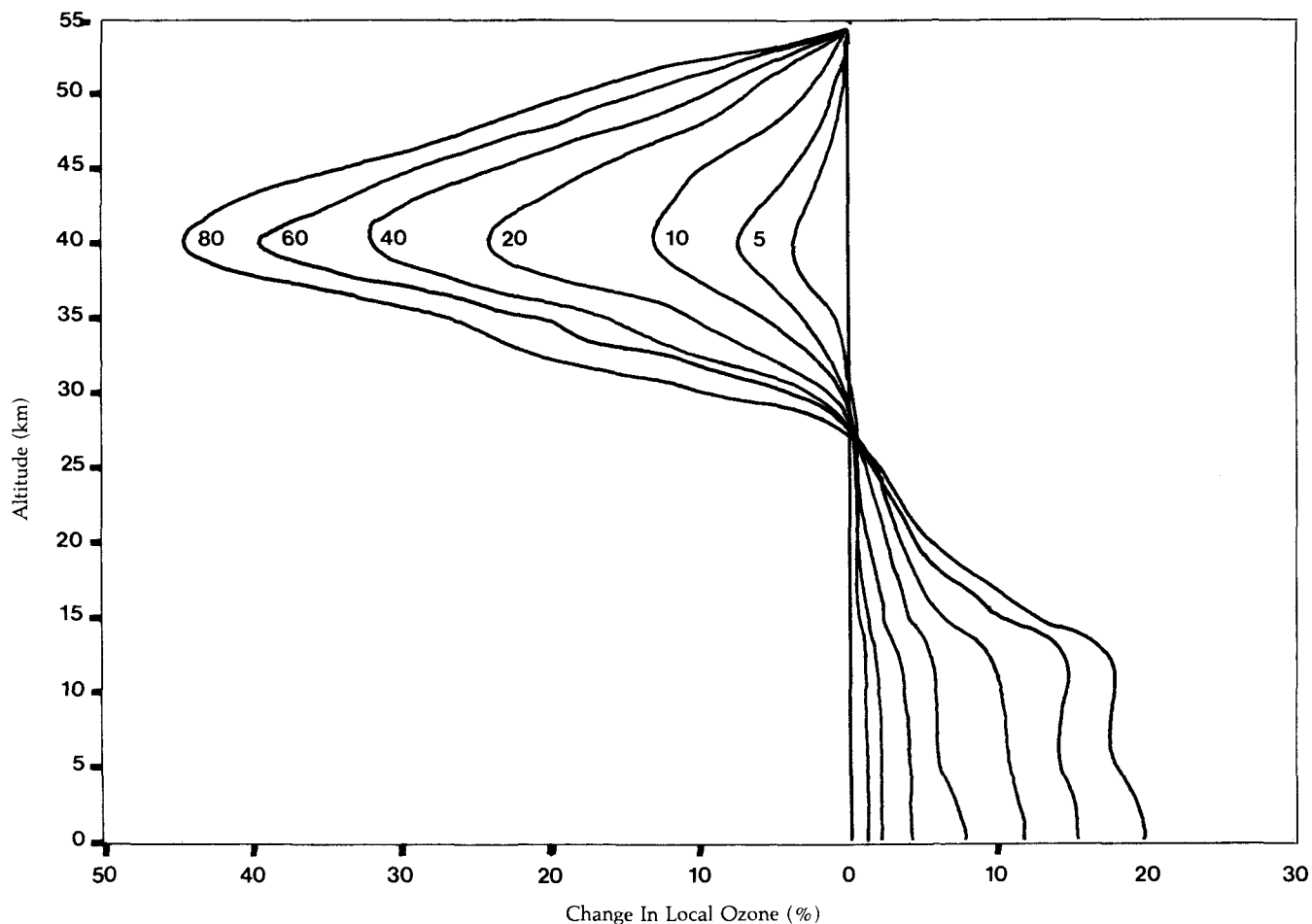


Calculated percentage change in ozone at different altitudes over time (5 to 100 years) for a scenario assuming CFC emissions begin at 1980 rates and increase at 1.5% per year, $CH_4$ increases at 1% per year, $N_2O$ increases at 0.25% per year, and $CO_2$ increases at 0.5% per year, using the LLNL 1-D model with temperature feedback.

**Source:** NASA, *Present State of Knowledge of the Upper Atmosphere* (1986)

skin by a process that affects peoples of all colors.[27] So far, however, no researchers have ventured to estimate dose/response relationships or to identify the diseases and populations most likely to be affected.

To date, most plants have not been tested for response to increased UV-B exposure, but about two thirds of the roughly 200 that have show some sensitivity.[28] *(See Table 2.)* Field research on soybeans indicates that yields could decline by up to 25 percent with a comparable increase in UV-B.[29] Scientists have yet to determine whether lower levels of depletion produce damage.

Research also suggests that ozone depletion could affect aquatic organisms deleteriously.[30] Some species (including commercially valuable anchovy larvae) have

developed UV-B tolerance to current exposure levels; with greater depletion, larvae could develop abnormally or fish populations could relocate away from the water's surface, altering the marine food chain.

Recent studies indicate that increasing UV-B would exacerbate smog in some urban areas.[31] This research relates the intensity of UV-B flux to the photolysis of formaldehyde, a product of incomplete combustion, which triggers the formation of the "radicals" that generate photochemical smog—a process that accelerates as temperatures rise. The precise composition of smog depends on the incremental change in temperature and the balance of pollutants in the atmosphere. One modelling experiment found that

**Figure 7.** Estimated Ozone Change by Latitude
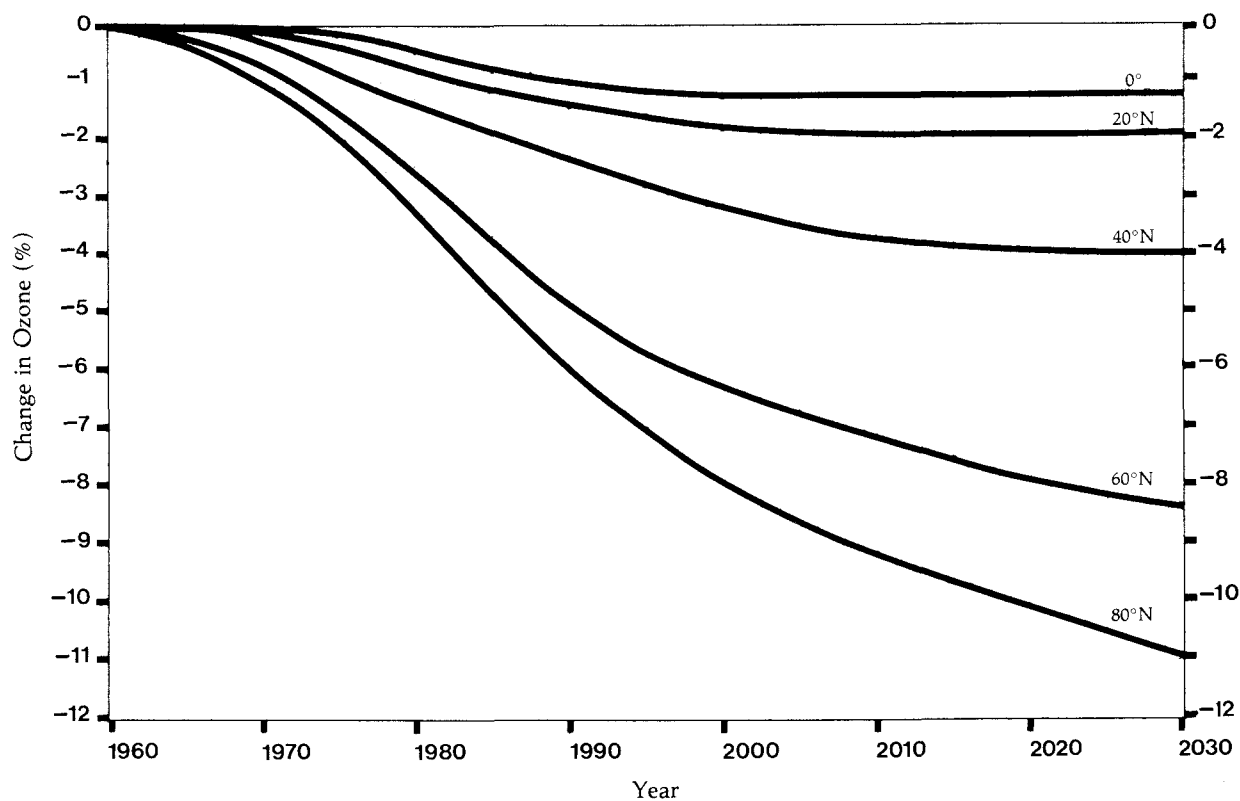


Changes in total atmospheric ozone over time for various latitudes assuming constant releases of CFCs at 1980 levels, $N_2O$ increases 0.25% per year, $CH_4$ increases 1.0% per year. The results are for the Spring in the case of 1980.

Source: F. Stordal and Ivar Isaksen, "Ozone Perturbations Due to Increases in $N_2O$, $CH_4$, and Chlorocarbons: Two-Dimensional Time-Dependent Calculations," in J. Titus, ed., *Effects of Changes in Stratospheric Ozone and Global Climate* (U.S., EPA, Washington: 1986)

smog would increase 30 percent or more in Philadelphia and Nashville, but much less in Los Angeles, if stratospheric ozone decreased by 33 percent and temperature increased by 4 °C.[32] Ozone is also predicted to form earlier in the day, causing larger populations to be exposed.

Another economically important effect of ozone depletion is accelerated degradation of some plastics and paints. This deterioration might be mitigated at some expense if improved chemical stabilizers are developed.[33] Without such stabilizers, cumulative damage to polyvinyl chloride by 2075 could equal $4.7 billion.[34]

The vertical distribution of ozone does not affect how much UV-B reaches the earth, so changing the pattern would not have the same effects as ozone depletion.

Nonetheless, such changes could affect climate.[35] In the lower stratosphere, the predicted increase in ozone will contribute to the greenhouse effect. Redistributing ozone would also affect atmospheric temperatures and, therefore, water vapor concentrations, both of which influence climate.

In short, changes in ozone are intimately linked to the greenhouse effect.[36] A July 1986 statement by the WMO/ICSU/UNEP (World Meteorological Organization/ International Council of Scientific Unions/United Nations Environment Programme) Advisory Group on Greenhouse Gases concluded that "Both with regard to future scientific research efforts as well as the analysis of possible societal responses . . . these two environmental problems should be addressed as one combined problem."

11

**Table 1.**                    Effects of Ultraviolet Radiation on Human Health

| | |
|---|---|
| Acute<br>  Sunburn<br>  Thickening of the skin<br><br>Chronic<br>  Aging of skin, thinning of epidermis<br><br>Carcinogenic<br>  Nonmelanoma skin cancer<br>    Basal cell carcinoma<br>    Squamous cell carcinoma<br>  Malignant melanoma | Eye disorders<br>  Cataracts (probable relationship)<br>  Retinal damage<br>  Corneal tumors<br>  Acute photokeratitis ("snow blindness")<br><br>Immunosuppression (possible)<br>  Infectious diseases of the skin (e.g., Herpes simplex)<br><br>Conditions Aggravated by UV Exposure<br>  Genetic sensitivity to sun-induced cancers<br>  Nutritional deficiences (kwashiorkor, pellagra)<br>  Infectious diseases (e.g., Herpes simplex)<br>  Autoimmune disorders (e.g., lupus erythematosus) |

*Sources:* E. Emitt, "Health Effects of Ultraviolet Radiation," in J. Titus, ed., *Effects of Changes in Stratospheric Ozone and Global Climate* (1986); EPA, *Assessment of the Risks of Stratospheric Modification* (1986); NAS, *Causes and Effects of Changes in Stratospheric Ozone* (1984).

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**Table 2.**                    Summary of UV-B Effects on Plants

| Plant Characteristic | Enhanced UV-B |
|---|---|
| Photosynthesis | Decreases in many $C_3$ and $C_4$ plants |
| Leaf conductance | No effect in many plants |
| Water use efficiency | Decreases in most plants |
| Dry matter production and yield | Decreases in many plants |
| Leaf area | Decreases in many plants |
| Specific leaf weight | Increases in many plants |
| Crop maturity | No effect |
| Flowering | May inhibit or stimulate flowering in some plants |
| Interspecific | Species may vary in degree of response |
| Intraspecific differences | Response varies among cultivars |
| Drought stress | Plants become less sensitive to UV-B but not tolerant to drought |

*Source:* Alan Teramura, "Overview of Our Current State of Knowledge of UV Effects on Plants," in J. Titus, ed., *Effects of Changes in Stratospheric Ozone and Global Climate* (EPA; Washington, 1986)

# II. CFC's Uses, Controls, and Substitutes

CFCs are used principally as aerosol propellants, as refrigerants, as agents for foam blowing, and as solvents. How much of the different CFCs is produced and which purposes they serve vary enormously around the world. (See Figures 8 a-b.) Use of these potential ozone-depleting substances is, however, concentrated primarily in the United States and the western industrialized nations. (See Table 3).

**Table 3.** Estimated 1985 World Use of Potential Ozone-Depleting Substances (In thousands of mt[a])

| Chemical | World | United States | Other Reporting Countries | Communist Countries |
|----------|-------|--------------|--------------------------|--------------------|
| CFC-11 | 341.5 | 75.0 | 225.0 | 41.5 |
| CFC-12 | 443.7 | 135.0 | 230.0 | 78.7 |
| CFC-113 | 163.2 | 73.2 | 85.0 | 5.0 |
| Methyl chloroform | 544.6 | 270.0 | 187.6 | 87.0 |
| Carbon tetrachloride | 1,029.0 | 280.0 | 590.0 | 159.0 |
| Halon 1301 | 10.8 | 5.4 | 5.4 | 0.0 |
| Halon 1211 | 10.8 | 2.7 | 8.1 | 0.0 |

[a]Metric tons.
Source: Hammit et al., *Product Uses and Market Trends*, p. 2

The United States, Canada, and Sweden banned most aerosol uses in the late 1970s. But since other countries did not, this application still represents almost a third of CFC 11 and 12 use by countries surveyed in the annual Chemical Manufacturers Association report (companies representing about 85 percent of estimated global production). The United States and Japan also use large amounts of CFC 12 for automobile air conditioning. Foam blowing is the major use of CFC 11, while almost all CFC 113 is used as a solvent.
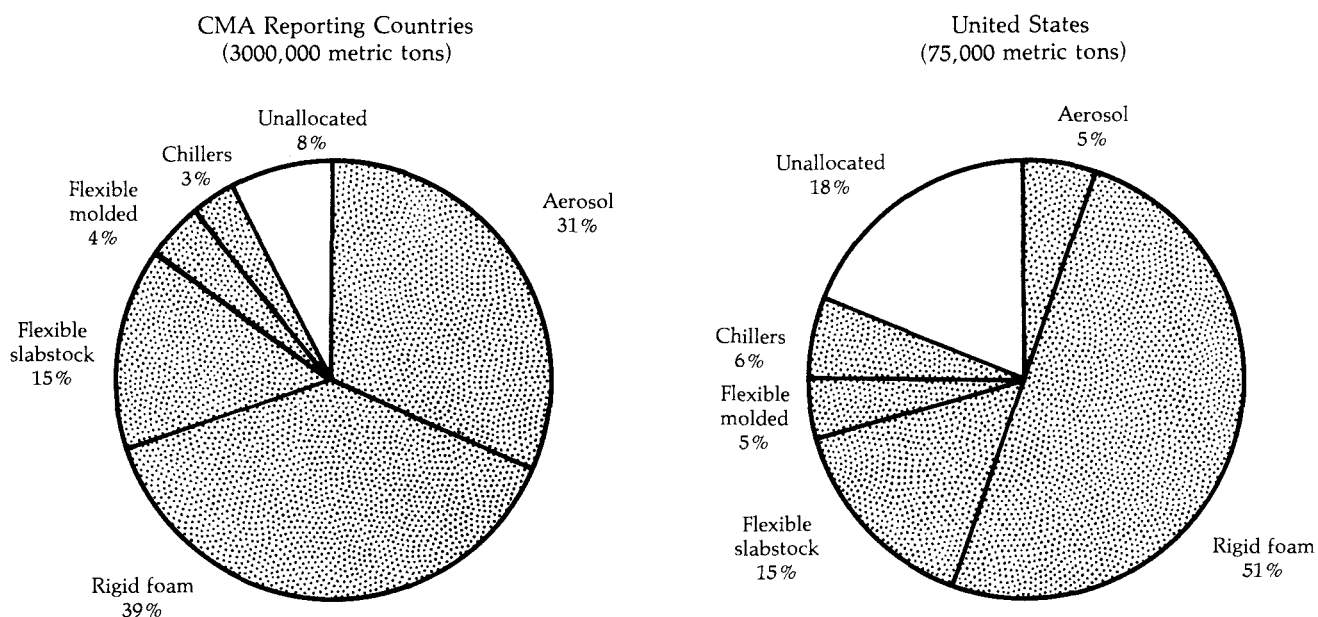
Global use of CFC 11 and CFC 12 has increased steadily over time, though growth rates vary markedly by use and country. (See Figures 9 a-b.) Between 1958 and 1983, average *annual* production grew approximately 13 percent. In theory, such growth could continue. Supplies of the raw materials needed for future production are more than adequate: identified reserves of fluorspar, the critical material, could meet projected demand through at least 2030 and probably, much longer.[37]

Different emission rates are associated with CFC uses. Aerosols create emissions virtually immediately, while most other uses emit CFCs gradually. Emissions from rigid foams may be glacially slow since the CFCs remain stored until the foam is crushed: large amounts of CFCs are, in effect, "banked" for future release unless that release is somehow prevented.

*Emissions of CFCs can be reduced through four basic methods: reducing operating losses; recovering and recycling during production or at the point of use; substituting CFC formulations less threatening to the stratosphere or switching to processes or products that require no CFCs.*

Emissions of CFCs can be reduced through four basic methods: reducing operating losses; recovering and recycling during production or at the point of use; substituting CFC formulations less threatening to the stratosphere, such as CFC 22 or CFC 134a; or switching to processes or products that require no CFCs.[38] The cost and availability of these substitutes varies enormously; some are already vigorous competitors with CFCs, while others will require further research and will probably be expensive.

**Figure 8a.** Estimated Use of CFC-11 by Product, 1984, U.S. and Countries Reporting to the Chemical Manufacturers Association (CMA)*

CMA Reporting Countries
(3000,000 metric tons)

Unallocated 8%
Chillers 3%
Flexible molded 4%
Flexible slabstock 15%
Aerosol 31%
Rigid foam 39%

United States
(75,000 metric tons)

Aerosol 5%
Unallocated 18%
Chillers 6%
Flexible molded 5%
Flexible slabstock 15%
Rigid foam 51%

* Percentages are Estimates Reflecting Numerous Uncertainties

**Figure 8b.** Estimated Use of CFC-12 by Product, 1984, U.S. and Countries Reporting to the Chemical Manufacturers Association (CMA)*

CMA Reporting Countries
(365,000 metric tons)

Unallocated 22%
Aerosol 32%
Miscellaneous 7%
Home refrigerators 3%
Chillers 1%
Retail food refrigeration 3%
Mobile air conditioning 20%
Rigid foam 12%

United States
(135,000 metric tons)

Aerosol 4%
Rigid foam 11%
Unallocated 31%
Miscellaneous 10%
Home refrigerators 2%
Chillers 1%
Retail food refrigeration 4%
Mobile air conditioning 37%
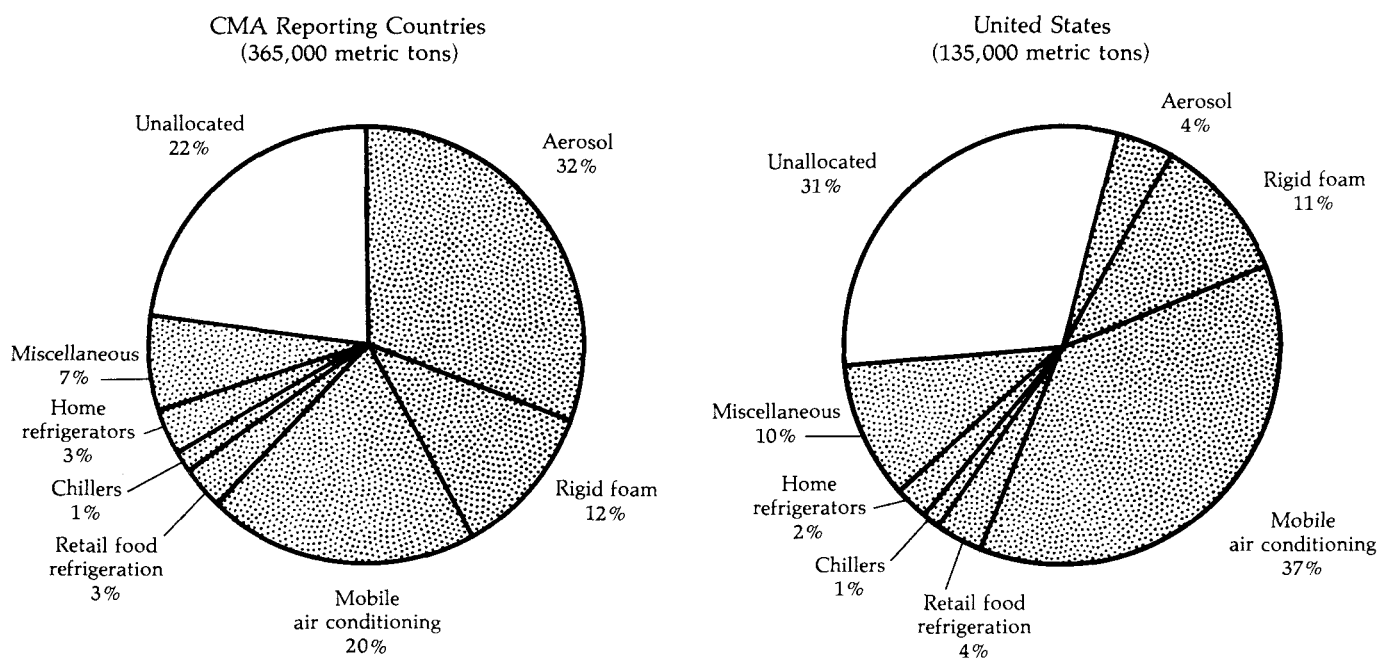
* Percentages are Estimates Reflecting Numerous Uncertainties

**Source:** J. Hammit et al., *Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000.* (Santa Monica, CA: Rand, 1986), p.5.
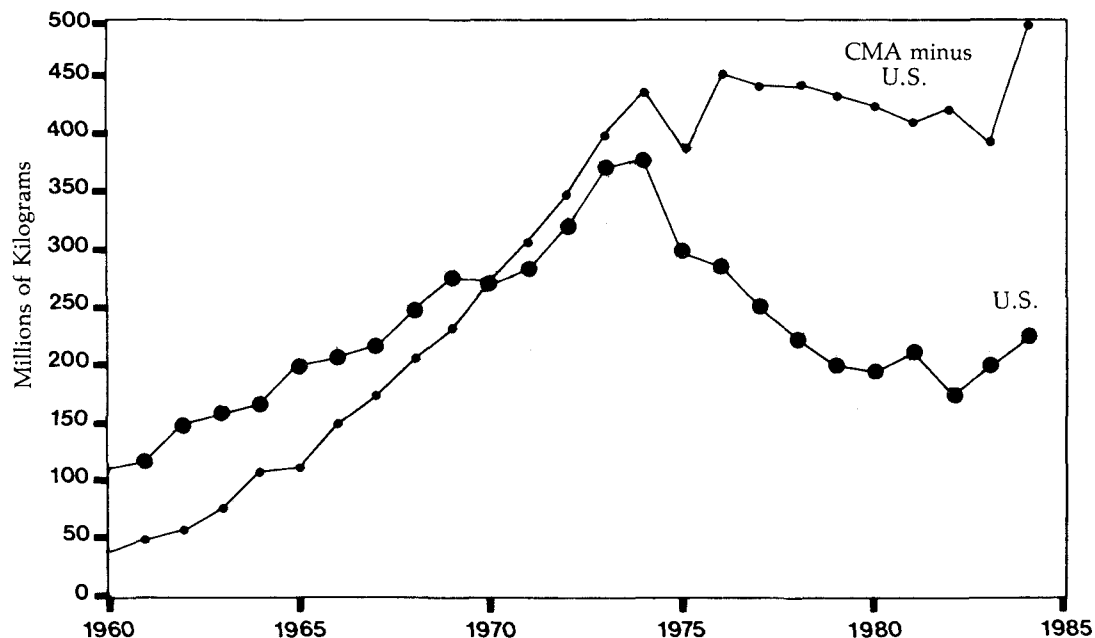
**Figure 9a.** CFC-11 and CFC-12 Historical Production for Countries Reporting to the Chemical Manufacturers Association (CMA)
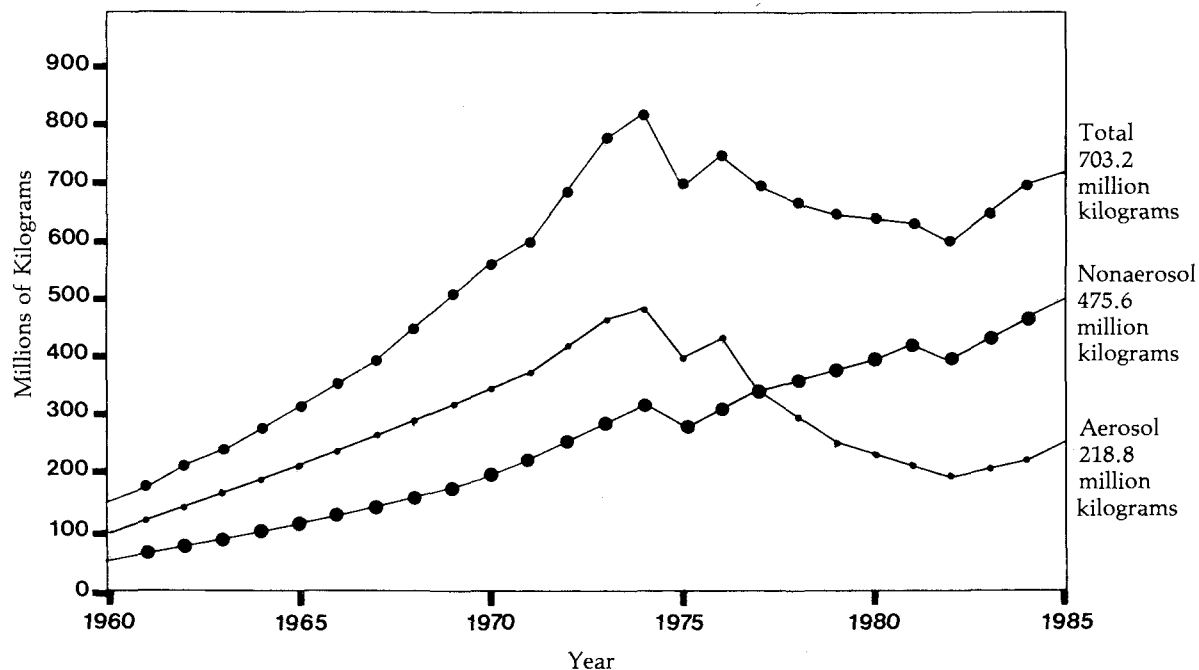
**Figure 9b.** Historical Selected Region Production of CFC-11 and CFC-12

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## 1. Increasing Efficiency and Reducing Operating Losses

One of the simplest ways to reduce CFC emissions is to design and operate equipment to reduce losses.[39] For some applications, leakage represents a significant share of total production. For example, almost one third of all CFC 12 used in the United States is for automobile air conditioning, of which an estimated 30 percent is lost in routine leakage and another half escapes during servicing. The remainder is emitted when units are first charged, subsequently serviced, or eventually scrapped.

Leakage losses could be reduced by, for instance, redesigning equipment to reduce the number of joints, tightening seals and valves, and taking similar measures. Stationary refrigeration and air conditioning systems, which employ such measures, typically leak much less than other systems.[40] In vehicular systems, the technical problems are somewhat more complicated, and the current price of CFCs isn't high enough to induce consumers and manufacturers to make the necessary adjustments.

Leakage from rigid polyurethane foams is widely considered negligible, particularly if the material is sheathed.[41] However, leakage will eventually occur during disposal unless the material is buried or burned, which prevents release of CFCs to the stratosphere. CFCs in rigid foams can be destroyed through incineration or in catalytic burners, but the by-products released corrode incinerator linings.[42]

The amount of CFCs used in refrigerators is also affected by the type of compressor employed: reciprocating compressors use only one third to one half the refrigerant that rotary compressors do. With advances in equipment design, most refrigerators and chillers need ever smaller amounts of CFCS, a trend that is likely to continue.

## 2. Recovery and Recycling

Opportunities for reducing CFC emissions by recovering the compound and by cleaning the captured chemical for reuse are substantial. Both approaches are in use today, primarily in operations centralized and large enough to justify the cost of the necessary additional equipment. The economics and practicality of recycling pose a greater barrier for such small decentralized uses as motor vehicle air conditioners.[43]

For reducing emissions of CFC 113 used for degreasing and cleaning, recovery and reclamation offer significant opportunities. Recovery is possible for some processes with in-house distillation equipment that boils off, condenses, and collects the solvent for reuse. The contaminated gases can then be cleaned with activated carbon.

CFCs can also be recycled from vehicular air-conditioning systems. A study for EPA concluded that

such recycling would become economically attractive only if the price of CFC 12 rises several-fold. Still, several small firms now sell recycling systems for use with large centralized systems and vehicle fleets, such as city bus depots.[44]

Almost all the CFC 11 used to manufacture flexible foams is lost in venting during production. Fortunately, recapture and recovery through carbon filtration can reduce operating losses by 50 percent, according to tests by a Danish firm.[45] The investment pays for itself in only two years given current CFC prices, but payback takes much longer from small plants. Similar techniques can at least halve emissions of CFC 12 used in the manufacture of rigid foams and can be economically justified for large plants at current CFC prices.

## 3. "Safe CFCs" (Formulations with Hydrogen or Without Chlorine)

As noted, some formulations of CFCs present little or no threat to the ozone layer. Several now identified could substitute for CFC 11 and CFC 12, greatly reducing or eliminating the threat to the ozone layer.[46] (See Table 4.) Some of these products could be substituted with little or no change in existing equipment, though possibly at a cost several times as great as CFC 11 and CFC 12.

One commercially available option is CFC 22, which degrades so rapidly in the atmosphere that it is only about one-fifth as powerful as CFC 12 in depleting ozone. CFC 22 could be used in air conditioning and refrigeration instead of CFC 12, though existing equipment would have to be redesigned first. Systems would have to be heavier too, a disadvantage for automobile applications.

CFC 22 is used today in home air conditioning and was used in some vehicular air conditioning until replaced by lighter and less expensive equipment in the early 1970s. CFC 502, a blend of CFC 22 and CFC 115, is widely used by food retailers for low-temperature refrigeration. Although this refrigerant is more expensive than CFC 11 and CFC 12, it could be used economically for a wider range of applications than it now is. The Air-Conditioning Wholesalers recently adopted a resolution urging a switch to these substitute CFCs in new air conditioning equipment.[47]

DuPont, the largest U.S. manufacturer of CFCs, announced in September 1986 that it could produce substitute CFCs in commercial quantities in five years given adequate regulatory incentives.[48] This would allow time for toxicity testing and other necessary regulatory approvals, as well as for organizing the necessary equipment. DuPont did not indicate the expected cost, and it may be that other alternatives would be less expensive for most markets. Nevertheless, the availability of safe CFCs that can be substituted

**Table 4.** Status of Alternative Fluorocarbons

| Fluorocarbon No. & Formula | Potential Application | Manufacturing Process | Flammable | Toxicity |
|---|---|---|---|---|
| 11 $CCl_3F$ | Blowing Agent, Refrigerant | Yes | No | Low |
| 12 $CCl_2F_2$ | Refrigerant, Blowing Agent, Food Freezant, Sterilant | Yes | No | Low |
| 113 $CCl_2FCClF_2$ | Solvent, Refrigerant | Yes | No | Low |
| 114 $CClF2CClF_2$ | Blowing Agent, Refrigerant | Yes | No | Low |
| 132b $CH_2C1CClF_2$ | Replacement for CFC-113; too strong a solvent; Dropped | No | No | Very Incomplete |
| 134a $CH_2FCF_3$ (a) | Replacement for CFC-12; Refrigerant, Others? | No | No | Incomplete Testing |
| 141b $CH_3CCl_2F$ | Replacement for CFC-11; Blowing Agent | Yes Developmental | Yes | Incomplete Testing |
| 142b $CH_3CClF_2$ | Blowing Agent, Refrigerant | Yes Limited | Yes | Low |
| 143a $CH_3CF_3$ (a) | Refrigerant | Not Commercial | Yes | Incomplete Testing |
| 152a $CH_3CHF_2$ (a) | Propellant; Refrigerant | Yes Limited | Yes | Low |

(a) Contains no Chlorine

*Source:* DuPont, 1986, based on information available in February 1986.

without radical changes in existing equipment represents a major step toward reducing risks to the ozone layer.

fire regulations prohibit use of hydrocarbons in cosmetics sold in Japan.

## 4. Substitution of Non-CFC Products

Product substitutes exist for most CFC uses, though frequently some economic or performance loss is entailed and sometimes a health or safety risk. The United States and several other countries have already substituted hydrocarbon propellants for more than 90 percent of aerosols.[49] U.S. regulatory authorities consider the substitution highly successful. However, differences in the location and organization of the CFC industry and limitations on the use of hydrocarbon substitutes may preclude generalizations about comparable success in Europe and Japan. For example,

*The United States and several other countries have already substituted hydrocarbon propellants for more than 90 percent of aerosols. However, differences in the location and organization of the industry and limitations on the use of hydrocarbon substitutes may preclude generalizations about comparable success in Europe and Japan.*

For insulation, various product substitutions are possible. Cardboard packaging now competes with polystyrene foams, and several insulating materials are made without CFCs, including fiberglass and cellulose. Although less effective for a given volume, substitute insulators are cheaper, and they are already preferred for such applications as residential construction in some regions.

Some flexible foams are produced with methylene chloride, though health risks may limit use of this toxic chemical. Reportedly, a new Belgian process costs less than CFCs and allows production of all densities of foam with no auxiliary blowing agent. Some molded foams can also be produced in whole or in part with carbon dioxide as a blowing agent. About one third of nonurethane foam is blown with pentane, though its flammability and regulations related to its possible role in smog formation limit its use. In home refrigeration, ammonia was widely used before CFCs were developed, but it is too toxic to be considered safe.

Several solvents can substitute for many uses of CFC 113, including methyl chloroform, methylene chloride, and, for some purposes, de-ionized water. Some of these substitutes are regulated, however, and none are currently suited for some applications. Some electronics components could not be made of plastics without CFC 113. On the other hand, a U.S. ban on land disposal of chlorinated solvents that took effect in November 1986 and the high cost of incinerating CFC 113 (because it contains fluorine) have created strong incentives for recycling and for developing substitutes.

Substitute technologies are also emerging for some other uses. For example, experimental vacuum panels developed for insulating refrigerators and other appliances greatly outperform rigid foams made with CFCs.[50] Several European and Japanese companies are actively developing this technology, and commercial use may occur soon.

A small Florida company also recently reported successful tests of a high-efficiency air conditioning compressor technology using low vapor-pressure hydrocarbons.[51] The developer claims that the technology is also more energy efficient and presents fewer leakage problems than comparable CFC-based systems. However, the system has not been commercially tested.

## Putting It All Together

Despite the availability of information concerning cost and feasibility of substitutes for many uses of CFCs, assessing the total cost and feasibility of methods for reducing CFC emissions remains surprisingly difficult. One problem is major gaps in our knowledge of how CFCs are used. For example, a recent study of CFC uses for EPA by the Rand Corporation, summarizing more than five years of analysis, was unable to identify more than 20 percent of CFC 11 and CFC 12 use reported in the CMA survey.[52] Therefore estimating the cost and feasibility of emission reductions can only be done as rough approximations and not precise calculations.

The Rand analysts estimated that raising CFC prices in the U.S. up to $5 a pound—more than several times recent levels—would reduce use of CFC 11 by 6 to 16 percent, CFC 12 by 6 to 35 percent, and CFC 113 by 75 to 80 percent.[53] This relative insensitivity to price increases (except for CFC 113) implies great difficulty in substitution for CFCs in the short-run. Our analysis, supported by discussions with other industry experts, indicates that the potential for substitution is much greater. As shown in Table 5, cuts of between 25 and 90 percent are feasible in all major uses of CFC 11, CFC 12, and CFC 113 within five years at a cost of less than $5 per pound.

The most important reason we differ from Rand is the DuPont announcement that a "safe" CFC could be produced for a price unofficially expected to be five to ten times current price levels—close to or less than $5 per pound. Such a substitute represents a maximum cost alternative for most existing applications. Second, Rand omitted some known options which require redesign of equipment—particularly switching to CFC 22 in mobile air-conditioning and reducing venting losses. Third, Rand predicated its findings on the assumption that only methods already widely commercially tested would be used. Our analysis includes methods commercially available but not in widespread use, such as recycling motor vehicle air-conditioning refrigerant.

The cost of a $5 per pound tax applied to current use would be roughly several billion dollars. However, we doubt this amount would ever be paid because of the rapid introduction of substitutes and measures to use CFCs more efficiently. Moreover, even this amount would have relatively little effect on the price of final goods and services purchased by consumers. For example, the price of an air conditioner or refrigerator might rise by about $10—barely perceptible on items costing hundreds of dollars. We believe most consumers would consider this an acceptable charge to help protect the ozone layer.

While we have assumed some technological evolution, our estimates of likely innovation in response to economic incentives still seems conservative. There are few substitutes for some CFC uses now because no one has an incentive to produce them. Much as opportunities to improve energy efficiency magically appeared year after year following the tripling of energy prices, CFC price increases will produce new CFC substitutes as well. Indeed, use of energy, like CFC use, historically tracked GNP—until the large price rise that began in 1973. However, without a stiff tax, chemical companies may be unwilling to invest in the production of known, relatively expensive chemical substitutes.

The key to innovation is to increase the price of CFCs by taxation or regulation. This approach obviously requires government action.

**Table 5.**  Potential Short-Term Reductions in Emissions of Major CFCs for Less than $5 per Pound

| Application | Est. 1985 Global Use (in thousands mt) | Methods for Reducing Emissions |
|---|---|---|
| Aerosols | 93.7 (CFC-11)<br>115.6 (CFC-12) | replacement by hydrocarbons & non-aerosols<br>CUT: 90% |
| Rigid foams | 115.8 (CFC-11)<br>42.8 (CFC-12) | Substitute blowing agents; recycling<br>CUT: 50% |
| Other foams | 57 (CFC-11) | Substitute blowing agents; recycling<br>CUT: 50% |
| Refrigeration & Air Cond. | 9.9 (CFC-11)<br>24.9 (CFC-12) | Substitute refrig; recovery at disposal<br>CUT: 25% |
| Mobile Air Cond. | 73.4 (CFC-12) | reduced venting; recycling; tighter seals; CFC-22 test gases<br>CUT: 25% |
| Solvents | 163.2 (CFC-113) | Recover and recycling; substitute solvents<br>CUT: 80% |
| Miscellaneous, Unallocated | 23.6 (CFC-11)<br>108.3 (CFC-12) | CUT: 25%[a] |
| Communist countries | 41.5 (CFC-11)<br>78.7 (CFC-12) | CUT: 33%[a] |

[a]: Based on conservative assumption regarding actual mix of uses

*Source:* Authors' estimates based on sources cited in text.

# III. Regulatory Policy Issues

The Vienna Convention for the Protection of the Ozone Layer and the ongoing U.S. regulatory proceedings are the most recent stages of decade-long governmental deliberations on ozone depletion. Understanding these current issues requires a brief review of past actions.

## Past Government Action to Protect the Ozone Layer

The ozone depletion problem was first hypothesized in 1974, and representatives of the major CFC-producing nations met several times in the next four years.[54] The major application of CFC 11 and 12 in that period was for aerosol propellants, the use of which many countries cut back or largely eliminated as consumer preferences changed in response to adverse publicity about CFCs and aerosol sprays. Most of these bans and cutbacks were adopted unilaterally, though all members of the European Economic Community agreed to reduce aerosol uses by 30 percent from 1976 levels and to prohibit increasing CFC production capacity.

Cutbacks in aerosol uses of CFCs alone reduced CFC emissions and risks to the ozone layer for several years. Production of CFC 11 and 12 among CMA-reporting countries dropped by 26 percent between 1974 and 1982. However, gradual growth in non-aerosol uses was expected to eventually offset this reduction and model calculations in the late 1970s indicated the problem might be worse than first thought. *(See Figures 9a-b.)*

By 1979-80, governments were considering taking a harder line. In October 1980, EPA outlined a proposal for limiting total domestic CFC production to current levels—a no-growth concept. The agency proposed allocating the allowable production through purchased permits that would have forced gradual reductions in uses of CFCs.[55] For both political and scientific reasons this proposal was never adopted. The Administration that took office in 1981 looked unfavorably on most regulation, and researchers' perceptions of the seriousness of the problem changed. Modelers reduced their estimates of depletion based on revised reaction

rates, and CFC producers and users argued that the risks did not justify the high costs of alternatives for non-aerosol uses, particularly when many other countries were still using CFCs for aerosol propellants. Industry argued that any further regulation should emerge from an international agreement.

While the EPA proposal languished, international discussions on further action continued.[56] A UNEP Governing Council Decision in April 1980 called on governments to reduce national use and production of CFCs. In May 1981, the same body established an Ad Hoc Working Group of Legal and Technical Experts to elaborate a Global Framework Convention for the Protection of the Ozone Layer. Following several years of negotiations, the Vienna Convention for the Protection of the Ozone Layer was signed in March 1985 by 20 countries with the blessing of both industry and environmental groups.

The Convention—some 21 articles and two technical annexes—spells out states' general obligation to control activities that "have or are likely to have adverse effects" on the ozone layer and to cooperate in scientific programs to better understand risks to the ozone layer. The annexes describe needed research and information exchange including CFC production data that few countries had heretofore reported. (The Soviet Union released such data for the first time at the September 1986 workshop.) The Convention creates a secretariat (a function at least temporarily served by UNEP) and procedures for bringing the signatories together. The Convention will enter into force once 20 countries ratify it, perhaps in 1987.

Participants at the Vienna Convention meetings also tried unsuccessfully to adopt a protocol for controlling CFCs—a proposal first made by Norway, Finland, and Sweden in April 1983. Later that year, the United States, Canada, and Switzerland proposed limiting the proposal to an international aerosol ban, which then became the Nordic position as well. (All these countries had for the most part already adopted aerosol bans.[57])

In this to-and-fro, the European Economic Community, major producers of CFCs, proposed an alternative protocol modeled after its own policy: a

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30-percent reduction in aerosol uses and a cap on future CFC production capacity.[58]

The proposals of the EEC and Nordic countries (the latter often referred to as the "Toronto Group" after a meeting in that city) each had some merits and limitations. A production capacity limit would cap total growth in CFCs, the ultimate environmental objective. However, the limit proposed would allow substantial growth based on existing excess capacity and possible opportunities to engineer production increases. It would leave producers and users very uncertain about the timing of reduction in supply—an objection U.S. industries emphasized in 1980 when EPA proposed a production cap. On the other hand, the Toronto Group proposal would have led to significant short-term reductions, but it offered no long-term solution as non-aerosol uses of CFCs continued to grow.

Various compromise positions were proposed, but a quick resolution appeared unlikely. Rather than further delay the Convention, the parties agreed to complete it and continue to discuss protocol issues. Subsequently, they decided to hold two workshops in 1986 to review the economic and policy questions associated with producing and controlling CFCs and to reconvene in March 1987. These workshops and the discussions that follow are intended to assure that all countries understand each others' assessment of the costs and benefits of different policies—in effect, an international risk assessment. This process is itself an important and unique outcome of the negotiations that led to the convention. Pending a decision on a protocol, a resolution accompanying the Convention urges states to control CFC emissions "to the maximum extent practicable."

Discussions as of October 1986 have produced some progress, even though governments were not required to take official positions. U.S. and European trade associations representing CFC users and producers now support the concept of limits on CFCs, though they have not advocated a specific figure.[59] DuPont, the largest manufacturer of CFCs, separately announced its

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*Momentum is building in favor of further regulation, particularly in the United States.*

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support for emissions limits and for undefined "incentives" to develop alternatives.[60] Less vocal representatives of affected European interests have also expressed increased interest in further regulation. While the ultimate outcome remains uncertain, momentum is building in favor of further regulation, particularly in the United States. In early November, the United States informed other nations of its support

for an immediate cap on CFC emissions at current levels and a "long-term" commitment to phase out all CFCs that threaten the ozone layer.

## Current Policy Issues

As of late 1986, decisions about controls on CFCs hinged on three key issues. First, what are the policy implications if growth in other trace gases offsets ozone depletion due to CFCs? Second, what is the risk of delaying regulation? Third, what is the most effective and workable form for regulation? In particular, which strategies prevent significant short-term emissions growth but also create economic incentives for the longer-term development of substitutes?

### 1. What Do Multiple Perturbation Scenarios Imply for Policy?

As noted, atmospheric model calculations that assume continued growth in $CO_2$, $CH_4$, and $NO_x$—called multiple perturbation scenarios—show much less ozone depletion than those that assume growth in CFCs only. Some critics of regulation assert that these results undermine the need for government action.[61]

This is faulty reasoning. Multiple perturbation scenarios do not describe a "natural" or "safe" atmosphere; substantial changes in the vertical and latitudinal profiles would still be a significant problem. Moreover, since all the gases at issue contribute to the greenhouse effect, the resultant global warming and economic damage could be very large.

If CFC growth rates are high, emissions of other trace gases would also have to grow faster than current trends to moderate their ozone-depleting effects. But, the faster such emissions increase, the more rapidly significant and irreversible climate change may occur. If, however, the buildup of $CO_2$ and $CH_4$, is restrained to control global warming, the moderating influence of these trace gases on ozone depletion caused by CFCs would be severely limited. The two problems, inextricably connected, should thus be analyzed together.

The authors analyzed the warming effects of the multiple perturbation scenarios presented in the 1986 NASA/WMO report on processes controlling atmospheric ozone.[62] *(See Figure 6.)* These scenarios were used because they are sometimes cited to show how trace gases moderate ozone depletion and because they were developed internationally by scientists to represent past experience and possible future trends. Our analysis illustrates the consequences of two time-dependent scenarios, one in which chlorine growth is 1.5 percent per year and the other 3 percent per year—less than recent experience. In addition, recent trends in emissions of $CO_2$, $N_2O$, and $CH_4$ are assumed to

continue. The methodology used is intentionally conservative so any possible warming is not overstated.

The two time-dependent scenarios of trace gas emissions were analyzed to determine roughly when the planet would be committed to an equilibrium warming that is radiatively equivalent to doubled $CO_2$ and a temperature rise of 1.5°-4.5°C. *(See Table 6 and Figure 10.)* In one NASA scenario, CFCs increase by 1.5 percent per year and the other gases more slowly; and the radiative equivalent of doubled $CO_2$ occurs in approximately 2050. In the other, which allows CFCs to grow twice as fast but is otherwise the same, the threshold is crossed in approximately 2040 and the equivalent of quadrupled $CO_2$ occurs by 2070. The lower curve of Figure 10 illustrates the direct radiative effects (i.e., without feedbacks) of $CO_2$, $N_2O$ and $CH_4$ in each scenario. The middle curve represents the additional radiative forcing due to 1.5 percent annual increase in CFC emissions. The top curve illustrates the warming due to 3 percent annual growth in CFC emissions.

**Table 6.** Equilibrium Warming Commitment from Trace Gas Buildup (Degrees Centigrade)

| Year | 1.5% CFC Growth Plus Other Trace Gases (1) | 3% CFC Growth Plus Other Trace Gases (1) |
|---|---|---|
| 1980 | 0.0—0.0 | 0.0—0.0 |
| 1990 | 0.1—0.4 | 0.1—0.4 |
| 2000 | 0.3—1.0 | 0.4—1.1 |
| 2010 | 0.5—1.6 | 0.6—1.8 |
| 2020 | 0.8—2.3 | 0.8—2.5 |
| 2030 | 1.0—2.9 | 1.1—3.4 |
| 2040 | 1.2—3.6 | 1.5—4.4 |
| 2050 | 1.5—4.4 | 1.9—5.6 |
| 2060 | 1.7—5.1 | 2.4—7.1 |
| 2070 | 2.0—6.0 | 2.9—8.8 |
| 2080 | 2.3—6.8 | 3.7—11.1 |
| 2090 | 2.6—7.8 | 4.6—13.9 |
| 2100 | 2.9—8.8 | 5.8—17.5 |

NOTES:
1. Both scenarios of trace gas buildup are derived from NASA (1986). They assume 0.5% per year increase in $CO_2$ concentration, 0.25% annual growth in $N_2O$, and 1% annual growth in methane. The low scenario assumes 1.5% annual growth in emissions of CFC-11 and CFC-12. The high scenario assumes 3% annual growth in CFC-11 and CFC-12.
2. Estimates of equilibrium warming commitment are based on the one-dimensional model of V. Ramanathan, R.J. Cicerone, H.B. Singh and J.T. Kiehl, "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research*, Vol. 90, No. D3 (June 20, 1985) pp. 5547-5566. Warming commitment due to increases in $CO_2$ concentration is scaled logarithmically, warming effects of methane and nitrous oxide are scaled in proportion to the difference in the square roots of the concentration in the perturbed and the reference (1980) atmosphere; the warming effects of the CFCs are scaled in a linear fashion.

These results imply enormous potential changes in global climate.[63] An average global warming of only 2°C would make the earth warmer than ever experienced by humankind and could change precipitation, wind

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*An average global warming of only 2°C would make the earth warmer than ever experienced by humankind and could change precipitation, wind patterns, soil moisture, and many other features of the global climate system.*

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patterns, soil moisture, and many other features of the global climate system. The sea level would also rise, with enormous effect on coastal populations and wetlands.
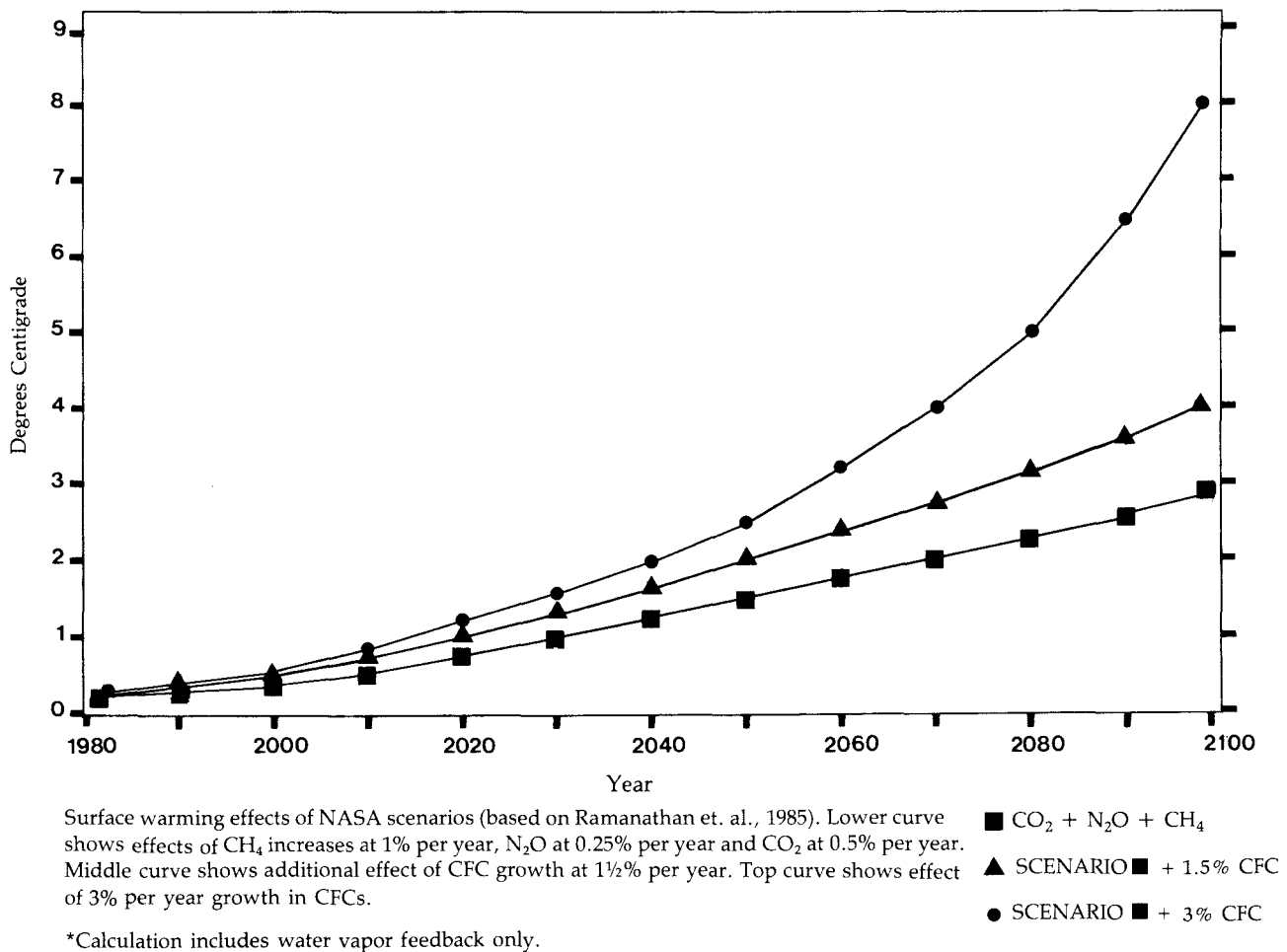
Some growth in greenhouse gases is likely, if only because their sources are not all known (particularly in the case of methane). However, scientists and policy-makers are increasingly calling for strategies to limit growth in greenhouse gases. An October 1985 report by more than 80 scientists from more than 20 countries and co-sponsored by three international organizations concluded that, despite many remaining uncertainties, a doubling of greenhouse gases from pre-industrial levels could have "profound effects on global ecosystems, agriculture, water resources, and sea ice." These experts recommended that "scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments."[64]

The precise quantitative results of WRI's analysis are not of critical importance. But the fundamental finding—that even low CFC growth rates (relative to present trends), coupled with the steady growth in

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*The assumption that continued growth in trace gases will moderate the ozone depletion expected from CFCs does not seem reasonable grounds on which to base policy.*

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other ozone-modifying substances, imply a potentially large global warming and climate change as early as the first half of the next century—is likely to prove robust and of considerable significance for policy. Accordingly, the rationale that continued growth in trace gases will moderate the ozone depletion expected from CFCs does not seem reasonable grounds on which to base policy.

**Figure 10.** Commitment to Global Warming With Limited Feedback Effects*



Surface warming effects of NASA scenarios (based on Ramanathan et. al., 1985). Lower curve shows effects of $CH_4$ increases at 1% per year, $N_2O$ at 0.25% per year and $CO_2$ at 0.5% per year. Middle curve shows additional effect of CFC growth at 1½% per year. Top curve shows effect of 3% per year growth in CFCs.

■ $CO_2$ + $N_2O$ + $CH_4$

▲ SCENARIO ■ + 1.5% CFC

● SCENARIO ■ + 3% CFC

*Calculation includes water vapor feedback only.

## 2. Why Should CFC Use Be Restricted Further Now?

Deciding when action to protect the ozone layer is necessary is a critical but difficult decision facing governments. Apart from the recent discovery of ozone depletion above the Antarctic, definitive proof of

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*Apart from the recent discovery of ozone depletion above the Antarctic, it is still unclear whether any change in natural ozone levels has occurred so far and, if so, whether CFCs are the culprits.*

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changes in natural ozone levels and of the primary role of CFCs is still lacking. Reducing emissions of CFCs from some uses will be costly and may risk other environmental damage. Some climate models also

indicate that net ozone will change little if CFC production does not exceed current global capacity, as it probably won't for a decade or more if recent trends continue. In these circumstances, some analysts argue that research should continue but that political action is not yet necessary. They agree with a European industry trade association that "Existing measures and review procedures are adequate in the short to medium term and therefore no [restriction on CFCs] is needed at the present time."[65]

Both environmental and economic problems vex this wait-and-see approach. If the only policy adopted is a production cap on CFC 11 and 12, substantial depletion is possible because of growth in CFC 113 and other ozone-depleting substances.[66] Depletion is also predicted if $CH_4$, $CO_2$, and other greenhouse gases do not continue growing at recent rates. Small changes in total ozone may disguise much larger reductions in ozone by latitude and altitude—large environmental risks independent of changes in total ozone.

A wait-and-see policy also presumes that changes will be gradual and verifiable, so that "actions can be taken

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at any time" without risking serious injury. The sudden unexplained appearance of the seasonal "ozone hole" in the Antarctic demonstrates the fallacy of this assumption. Smaller changes are much more difficult to verify and distinguish from natural swings. Quite possibly, large global changes will be irreversible before scientists can establish conclusively that depletion is occurring.

*Quite possibly, large global changes will be irreversible before scientists can establish conclusively that depletion is occurring.*

Decision-makers must also consider that substantial additional releases of chlorine from CFCs now stored in rigid foams, refrigerators, and other sealed uses will be almost inevitable. For example, releases of CFC 11 and 12 from companies reporting to the Chemical Manufacturers Association totalled 630 million kilograms in 1984, but cumulative unreleased production amounted to 1,534 million kilograms. Almost all of this amount is difficult to recover and will eventually be released, albeit slowly and gradually.

Another problem to be faced is that CFC emissions cannot be reduced instantly. The transition to substitutes and controls will take time. If nothing is done until ozone damage is upon us, governments will still need time to implement policies and industries time to switch to substitutes. As a result, substantial additional emissions could occur for many years after a policy decision is made.

All in all, the serious environmental risks associated with a wait-and-see policy make it inadvisable. Sensible policy dictates a more cautious approach. This philosophy is reflected in Section 157 of the Clean Air Act, which requires action if any substances "may reasonably be anticipated" to endanger the ozone layer.

Allowing increased CFC use while research continues also has an economic price. The timing and scope of the actions ultimately needed, if any, depend on CFC growth rates: the faster emissions increase, the sooner

*The faster emissions increase, the sooner actions may be needed and the more draconian they must be to keep concentrations within desired bounds.*

actions may be needed and the more draconian they must be to keep concentrations within desired bounds. The rate of growth in CFCs is therefore a critical but highly uncertain factor.

Attempts to project the rate of growth in CFC emissions are riddled with uncertainties. Historical experience suggests that production of potential ozone-depleting substances will grow with economic activity. Allowing for a range of economic growth and for variation in the growth of specific end uses produces wide-ranging possibilities—from near zero to more than 5 percent annual growth to the year 2000.

Some industry representatives argue that the mere threat of regulation limits the attractiveness and likelihood of further investment in new CFC production capacity. When the threat of regulation triggers or follows changes in consumer preference—as it did with aerosols in the 1970s—this makes sense.[67] However, if demand is growing rapidly, as it was in 1983-84, the threat of regulation alone may not deter investment. Since the capital cost of producing CFCs is small relative to total production costs, only a small rise in

*The threat of regulation did not prevent DuPont and Daikin from announcing in March 1986 a joint venture to build a larger new CFC production plant in Japan.*

CFC prices would be needed to allow rapid cost recovery, minimizing the risk to producers from future regulatory action.[68] Some plants could also be modified to produce CFC 22, which is not likely to be regulated. Indeed, the threat of regulation did not prevent DuPont and Daikin from announcing in March 1986 a joint venture to build a larger new CFC production plant in Japan.[69]

The possibility of growth in CFC demand greater than expected must also be considered. CFC growth rates in developing countries could be very rapid—even higher than economic growth—if, for example, a high priority is assigned to food storage and refrigeration.

The possibility of new or unanticipated demands for CFCs—such as the rapidly growing demand for CFC 113 as a solvent for cleaning computer circuit boards—further complicates long-term forecasting. Another energy crisis could also increase demand for insulation containing CFCs. While the timing and magnitude of new uses are inherently difficult to predict, CFCs' many attractive qualities—they are non-toxic, non-flammable, nearly inert, and efficient insulators and refrigerants—make new uses a serious consideration.

The impact of short-term growth on future policy is evident from Figure 11, which illustrates how different emissions-growth rates affect atmospheric concentrations of CFC 12. (The figure would have a similar but slightly different form for the other CFCs, reflecting differences in atmospheric lifetimes.) Because CFCs linger in the atmosphere for decades, emissions would have to be

**Figure 11.** CFC-12: Atmospheric Concentrations from Different Emission Trajectories (ppbv)
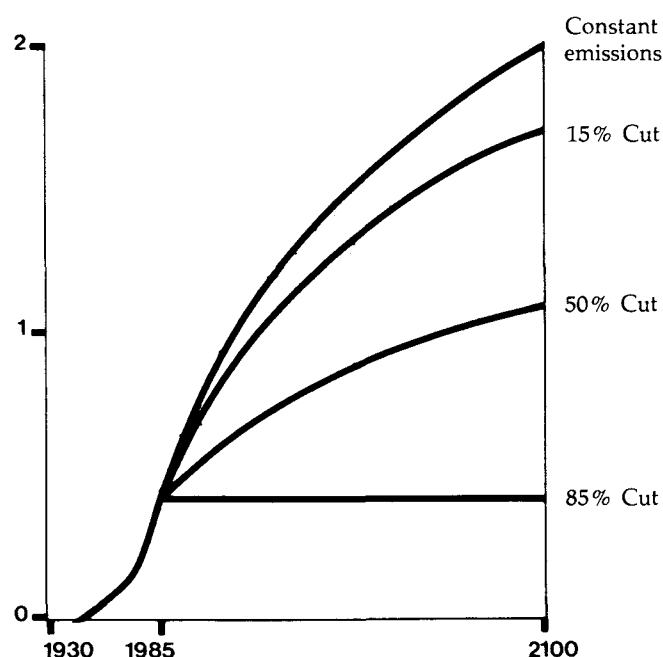


Atmospheric concentrations of CFC-12 will continue to rise unless emissions are cut. Holding emissions constant at today's level or even 15% or 50% lower would still allow atmospheric concentrations to grow. Only a cut of 85% or more could stabilize atmospheric concentrations.

cut by approximately 85 percent and then held constant to stabilize atmospheric concentrations. Even with constant emissions, atmospheric concentrations will continue to rise with any reduction smaller than 85%.

*The difference between 1.5, 3 percent, or higher growth in CFC emissions would radically affect the timing and severity of actions needed to keep chlorine concentrations below what are currently viewed as possible prudent upper bounds.*

Table 7 puts ozone depletion in another light by revealing the reduction in emission rates necessary in different years if atmospheric concentrations are to remain below 16 ppbv, in 2100, given different CFC growth rates. (16 ppbv was used because some models show significant nonlinearity in ozone depletion at this

concentration. The current concentration is about 2.5 ppbv.) If the global average increase in CFC emissions is even 1.5 percent, emissions must be reduced almost immediately to keep atmospheric chlorine below 16 ppbv in 2100. If no action is taken until 2030, growth must be reduced from 1.5 percent per year to 0.34 percent per year to stay below 16 ppbv in 2100.

If the near-term annual growth rate is three percent, still less than in recent years, far more stringent policies would be needed to stay below a 16 ppbv limit. (See Table 7.) Actions in 1990 would have to reduce the growth rate by a factor of nearly four, to 0.77 percent per year, to keep $Cl_x$ below 16 ppbv in 2100. In 2000, growth would have to fall to 0.42 percent. After this date, negative growth rates would be necessary to keep concentrations below 16 ppbv in 2100.

Most likely, the rate at which reductions might be required would affect control costs significantly because equipment would have to be phased out. Negative growth in CFC use was possible for stretches of several years in the past because aerosol uses of CFCs could be reduced with negligible (or at least tolerable) economic impacts. Since aerosol uses now represent a much smaller percentage of global CFC use while non-aerosol uses have been growing steadily, the opportunity for similar, relatively painless, reductions has diminished.

Clearly, growth in CFC emissions would radically affect the timing and severity of actions needed to keep chlorine concentrations below what are currently viewed as possible prudent upper bounds. *Adopting policy strategies that minimize the risk that rapid, dramatic*

**Table 7.** Effect of 1.5 and 3 percent CFC Growth on Timing and Severity of Emissions Reductions Necessary to Keep Chlorine Concentrations Below 16 ppbv in 2100

| Year Growth Reduced | Maximum Allowable Growth from 1.5% baseline* | Maximum Allowable Growth from 3% baseline* |
|---|---|---|
| 1990 | 0.73% | 0.77% |
| 2000 | 0.85% | 0.42% |
| 2010 | 0.73% | 0.00 |
| 2020 | 0.57% | negative |
| 2030 | 0.34% | negative |

Note: Unrestricted 1.5 percent CFC growth results in exceeding 16 ppbv $Cl_x$ in 2075; unrestricted 3 percent growth exceeds 16 ppbv $Cl_x$ in 2044.

*The Maximum Allowable Growth Rate is that rate of average annual increase in emissions which can be maintained in the year indicated without resulting in atmospheric concentrations of $Cl_x$ greater than 16 ppbv in 2100.

*Source:* Authors' calculations.

*reductions in CFC use will be needed later is therefore an important objective.*

Possibly, as some authorities argue, future growth in CFC emissions will not follow historical experience, but will instead be much less.[70] But, if growth is low, carefully crafted policy measures to reduce emissions could rather painlessly permit some limited CFC use in the future and insure that drastic reductions to keep atmospheric concentrations of chlorine at safe levels would not be required.

Of course, action can be taken at any time, but not with equivalent cost or risk. The sooner reductions are made, the more future uses will be protected.

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*Each pound of CFCs currently consumed in aerosol sprays may be a pound not available for much higher valued uses in the future.*

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Conversely, growing short-term CFC use for economically marginal applications, such as aerosols and retail food packaging, also circumscribes future opportunities to use CFCs for higher-value applications—such as the cleaning of plastic components for electronics. Each pound of CFCs currently consumed in aerosol sprays may be a pound not available for much higher valued uses in the future.

## 3. What Policy Strategies Will Probably Be Most Effective and Workable?

While obtaining international agreement on the need for further regulation of CFCs has been difficult, discussions of how fast and by what means restrictions should be achieved have been even more challenging. As noted, governments have naturally advocated policies that they have already adopted—a ban on new production capacity in Europe and a ban on aerosols in the United States, Canada, Sweden, and Norway. Fortunately, the two-year dialog initiated by the Convention has prompted participants to reconsider the relative merits of alternative policies.

International discussion has focussed on three basic issues: what limits should be placed on the production and use of CFCs now; how responsibility for meeting any such limits should be allocated among nations; and whether national policies are needed to implement global limits. Domestic consideration of these issues involves somewhat different issues, since each country will have to decide how to reduce its CFC use to stay within negotiated limits. Some strategies are difficult if not impossible to adopt on an international basis. For example, emission taxes have many desirable features but probably can only be implemented on a country by country basis.

## Limiting CFC Production and Use?

Although phasing out all uses of CFCs immediately would offer the most protection from ozone depletion and climate change, the risks may not justify the likely costs. Such proposals also invite political opposition. An international approach will work only if accepted by virtually all major CFC producers and users, and proposals based on sharp reduction probably won't meet this test. More realistic is adopting different strategies to meet both short and long-term goals, both international and domestic needs.

As explained here, policies implemented in the next few years will greatly affect the long-term cost of controls. The short-term need is for policies that will, at a minimum, reverse recent growth trends and begin steady reductions in CFC use, providing producers and users with a clear signal to seek out alternatives to CFCs.

Neither the EEC's capacity cap nor the United States' aerosol ban meets these objectives, particularly since any agreement may take years to implement and no additional action can realistically be expected for several years thereafter. Although constraining total production is conceptually sound, available excess capacity means that this approach will not be effective soon enough. Europe now has enough excess capacity to meet increased demand until perhaps the year 2010.[71] Recent sales data indicate that EEC sales of CFC 11 and 12 increased over 5 percent from 1982 through 1984.[72] Indeed, by the Commission's own analysis, no "bite" is expected until 1995 at the earliest.[73]

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*Recent sales data indicate that EEC sales of CFC 11 and 12 increased over 5 percent from 1982 through 1984.*

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The aerosol ban—which is not adequate to limit CFC growth and promote long-term substitutes—is also flawed. As the U.S. experience illustrates, eliminating any specific uses of CFCs, even all aerosols, can over time be offset by growth in other uses. Restricting only designated uses may even be counter-productive if remaining users interpret such policies as a license to use more and take more time to look for alternatives.

A better approach was suggested by Canadian representatives to the September 1986 workshop. Canada proposed an international cap on CFC *consumption* set at one third less than estimated current global *capacity* for producing CFC 11 and 12, which is about 1240 million kilograms. This would mean a global limit of about 800 million kilograms, roughly equal to recent global use. Consumption may be harder to monitor than production, but this policy does not unfairly favor countries with either more or less

production in place. Presumably, existing producers would compete for the permitted market. Depending on how this amount was allocated among nations, countries that now use large volumes of CFCs might have to make significant cutbacks.

According to our analysis, the optimal approach is to set the allowable total limit at one-third *below* estimated current production of CFC's. This level factors in the likelihood that any agreement may not take effect for several years as well as the opportunity to expeditiously eliminate use of CFCs for aerosols, food packaging, and other uses with commercially competitive substitutes. A commitment to short-term reductions of this magnitude should promote the development of substitutes so that over the longer-term—perhaps a decade—CFCs can be phased out with the least economic disruption.

We further advocate allowing a credit in the form of additional permitted consumption for amounts recaptured rather than obtained from new production. Any sound agreement will encourage recycling and incineration even though doing so will add to the administrative burden.

*Any sound agreement will encourage recycling and incineration even though doing so will add to the administrative burden.*

As for which chemicals any agreement should cover, most discussion has focussed on CFC 11 and 12. However, the United States has proposed a cap on all fully halogenated alkanes, including the halons as well as the listed CFCs. Use of CFC 113 for solvent applications is rapidly growing and now roughly equals the use of CFC 11 in the United States. CFC 113 may also be used as a substitute for some existing uses of CFC 11 and 12, so its use should therefore also be regulated. The halons, increasingly important, should also be included.

## Allocating Allowable Production

Whatever limit is imposed on production or consumption of CFCs, some allocation formula is needed to determine the amounts specific countries would be allowed. The Canadian proposal allocates 75 percent of permitted consumption to countries according to their GNP (reflecting current demand) and the remainder according to their population (to reflect potential demand). *(See Table 8.)*

On balance, the Canadian proposal allows for greatly increased use of CFCs in developing countries and basically calls for an immediate cutback in use by the

United States and Europe. This scheme is fair given that these countries have already obtained large economic benefits from CFCs and are largely responsible for the problem. The incentive to develop substitutes in the industrialized countries will also help produce alternatives for the developing countries, so much of the permitted allocation to the developing countries may never be used.

The potential for swapping usage rights raises difficult trade-offs. On the one hand, if trading were allowed, global use of CFCs would rise and a lower overall limit would be needed to achieve the same result as a no-trading policy. Trading also adds administrative complexity, and cheating is always possible. On the other hand, trading would encourage developing countries to sign the treaty and would promote recognition that the atmosphere is a scarce resource, with value to all nations. As a practical matter, the political desire to keep the treaty simple may discourage interest in a trading system, but practical means of implementing such a scheme should be carefully considered.

**Table 8.** Allocations Made Under Canadian Example (Millions Of Kilograms)

| | Canadian Example[a] | Current[b] (CFC-11 & 12) | Current[b] (CFC-11, 12, 113) |
|---|---|---|---|
| U.S. | 162.4 | 238.1 | 290.8[c] |
| EC | 138.4 | 218.8[d] | 259.5[e] |
| Japan | 57.2 | 57.5[f] | ? |
| East Bloc | 117.3 | 60.0[g] | ? |
| Canada | 17.9 | 21.0 | ? |
| China and Centrally-Planned Asia | 79.1 | 18.0[h] | ? |

a. Quotas computed using Canadian algorithm on population and GNP data for 1975 with a global emissions limit of 812 million kilograms.
b. Data for 1984 unless noted otherwise.
c. CFC-113 projected for 1983.
d. Has subtracted out exports which are 33% of total current production.
e. Also includes CFC-114.
f. Data for 1985.
g. USSR production capacity—does not include imports.
h. China only—does not include imports.

*Source:* EPA, 1986.

## National Policies for Implementing Global Limits

If global and national CFC limits are established (other than a ban on new production capacity), further national policies to reduce emissions may or may not be necessary. Producers could allocate the allowed amount

by charging enough to limit demand. In the United States, the Alliance for Responsible CFC Policy supports a voluntary approach based on actions by individual companies, an approach it believes will make regulation unnecessary. However, the Alliance cannot

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*If global and national CFC limits are established, further national policies may or may not be necessary.*

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predict what reductions will be achieved voluntarily, especially since reductions in demand will tend to lower CFC prices and reduce the incentive for substitution.

A consumption limit, even if enforced by regulation, may not alone promote short-term development and introduction of more costly chemical substitutes to CFCs since uncertainty surrounds opportunities for recycling, alternative products, and cheaper substitutes. Most producers will wait to see how the market responds before introducing products that may cost several times as much as current CFCs—witness DuPont's recent statement that it could produce CFC substitutes in commercial quantities in five years but that current policies make the expense unjustifiable.

The most effective means of assuring a minimum future price for CFCs is to tax them. Although other policies could cost less, the tax would affect a larger market—all uses of CFCs, not just future unmet demand. A tax would thus give producers a greater chance to recoup the cost of new chemicals. Of course, such a tax would have to be high enough to make expensive substitutes attractive. While our analysis is

necessarily preliminary given the lack of detailed data, a tax of $5 a pound, phased in over several years, should be more than adequate to make substitutes appealing.[74] This would not raise the cost of most CFC uses noticeably; the price of refrigerators and automotive air conditioners, for example, should not rise more than about $10 each.

A tax would also allow governments, rather than chemical producers, to benefit from the increase in selling price that may occur if consumption or production limits are set. The revenues captured could be used to support research on ozone depletion and climate change.

The perception of all parties to the international process is that taxation of CFCs by international agreement is well-nigh impossible. Nevertheless, adopting a tax in addition to setting consumption limits

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*Implementing a tax in addition to setting consumption limits is in the interest of individual countries poised to assume world leadership in the development of substitutes for CFCs.*

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is in the interest of individual countries poised to assume world leadership in the development of substitutes for CFCs. In the United States, several Senators have already proposed adopting policies to promote a total phase-out of CFCs, supported by restrictions on the import of lower-priced products made with CFCs.[75]

# IV. Conclusions

The scientific evidence and policy concerns outlined in this report have generated substantial momentum toward new restrictions on CFCs in recent months. In March 1986, EPA Administrator Lee Thomas stated that "We may need to act in the near term to avoid letting today's 'risk' become tomorrow's 'crisis'." In September, the Alliance for Responsible CFC Policy, announced support for a "reasonable global limit" on CFC growth. Large increases in CFC emissions, said the Alliance would be "unacceptable to future generations." In a separate statement, the DuPont company noted that "Neither the marketplace nor regulatory policy . . . has provided the needed incentives" to justify investments in alternatives to CFCs.

The scientific community has also added its voice to the call for action. The Advisory Group on Greenhouse Gases, sponsored by the World Meteorological Organization (WMO), International Council of Scientific Unions (ICSU), and United Nations Environment Programme (UNEP), stated in July 1986 that many uses of CFCs "can hardly be considered essential," and "international action to reduce release[s] . . . is technically possible, and if achieved, would be a valuable precautionary and preventive measure both to slow climate warming and to protect the ozone layer."

Even as the political consensus grows, so do potential opportunities to reduce CFC emissions. Chemical substitutes for fully-halogenated CFCs may become available in volume for most applications in about five years. Recycling and other low-cost alternatives are also available for some uses. However, these options won't be seized unless governments create incentives.

Building the international consensus necessary to phase out CFC emissions will take time. In the short term, it is more realistic to expect that participants in the Convention process can agree to reduce global CFC emissions by an amount roughly equal to current use in aerosol sprays, or about one third. The United States could meet this target despite its aerosol ban by adopting the measures suggested in Table 5. This move would be a major step forward and a clear signal to industry to begin searching for alternatives.

Individual actions by the U.S. and by other leading nations may also be necessary, even if an international protocol is adopted. Beyond the inherent difficulty of enacting any international agreement with meaningful restrictions, the Convention's effectiveness may also be compromised by the absence (or delayed participation) of some countries and the likelihood that not all ozone-depleting substances would be covered. Even bringing CFC production down to one third below recent levels—an ambitious goal—will not eliminate some significant environmental risks and may not induce investment in new chemicals, which will require considerable start-up capital and assurances of large markets.

Should further U.S action prove necessary, a tax should be imposed on CFCs, phased in over five years to assure producers of a future price high enough to justify producing chemical alternatives. (As noted, a final tax of $5 per pound would not cause the retail price of consumer goods to rise significantly but should justify immediate major investments in alternatives.) This tax should be supported by import restrictions to assure that domestic manufacturers do not suffer competitive disadvantage.

The challenge of protecting the ozone layer may be a harbinger of humankind's ability to address other long-term threats to the earth's future. Alternatives are available and the cost is modest. The issue is whether the needed political will can be marshalled before those costs rise.

# Appendix

## Atmospheric Chemistry and Ozone Concentrations: Some Basics

From World Meteorological Organization Global Ozone Research and Monitoring Project—Rep. No. 16, *Atmospheric Ozone 1985*, pp. 27–28.

Ozone is present in the earth's atmosphere at all altitudes from the surface up to at least 100 km. The bulk of the ozone resides in the stratosphere with a maximum ozone concentration of $5 \times 10^{12}$ molecule cm$_{-3}$ at about 25 km. In the mesosphere ($> 60$ km) $O_3$ densities are quite low ... Although $O_3$ concentrations in the troposphere are also less than in the stratosphere, ozone plays a vital role in the atmospheric chemistry in this region and also affects the thermal radiation balance in the lower atmosphere.

Atmospheric ozone is formed by combination of atomic and molecular oxygen.

$$O + O_2 + M \rightarrow O_3 + M \qquad (1)$$
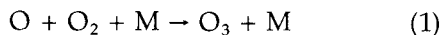
where M is a third body required to carry away the energy released in the combination reaction. At altitudes above approximately 20 km production of O atoms results almost exclusively from photodissociation of molecular $O_2$ by short wavelength ultraviolet radiation ($\lambda < 243$ nanometers):

$$O_2 + hv \rightarrow O + O \qquad (2)$$
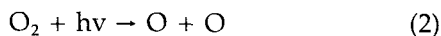
At lower altitudes and particularly in the troposphere, O atom formation from the photodissociation of nitrogen dioxide by long wavelength ultraviolet radiation is more important:

$$NO_2 + hv \rightarrow NO + O \qquad (3)$$
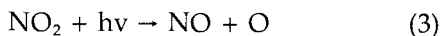
Ozone itself is photodissociated by both UV and visible light:

$$O_3 + hv \rightarrow O_2 + O \qquad (4)$$
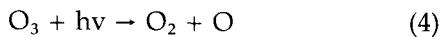
but this reaction together with the combination reaction (1) only serves to partition the 'odd oxygen' species between O and $O_3$. The production processes (2) and (3) are balanced by chemical and physical loss processes. Until the 1950s, chemical loss of odd oxygen was attributed only to the reaction:

$$O + O_3 \rightarrow O_2 + O_2 \qquad (5)$$
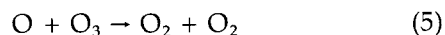
originally proposed by S. Chapman (1930). It is known that ozone in the stratosphere is removed predominantly by catalytic cycles involving homogenous gas phase reactions of active free radical species in the $HO_x$, $NO_x$, $ClO_x$, and $BrO_x$ families:

$$X + O_3 \rightarrow XO + O_2 \qquad (6)$$
$$XO + O \rightarrow X + O_2 \qquad (7)$$
$$\text{net:} \quad O + O_3 \rightarrow 2O_2$$
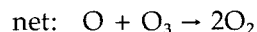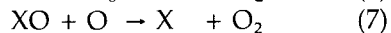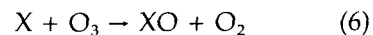
where the catalyst X = H, OH, NO, Cl and Br. Thus these species can, with varying degrees of efficiency, control the abundance and distribution of ozone in the stratosphere. Assignment of the relative importance and the prediction of the future impact of these catalytic species is dependent on a detailed understanding of the chemical reactions which form, remove and interconvert the active components of each family. This in turn requires knowledge of the atmospheric life cycles of the hydrogen, nitrogen and halogen-containing precursor and sink molecules, which control the overall abundance of $HO_x$, $NO_x$ and $ClO_x$ species.

Physical loss of ozone from the stratosphere is mainly by dynamical transport to the troposphere where further photochemically driven sources and sinks modify the ozone concentration field. Ozone is destroyed at the surface of the earth so there is an overall downward flux in the lower part of the atmosphere. Physical removal of ozone and other trace gaseous components can also occur in the precipitation elements and on the surface of atmospheric aerosols. Since most of the precursor and sink molecules for the species catalytically active in ozone removal in the stratosphere are derived from or removed in the troposphere, global tropospheric chemistry is a significant feature of overall atmospheric ozone behavior.

Numerical simulation techniques are used to describe and investigate the behavior of the complex chemical system controlling atmospheric composition, the models having elements of chemistry, radiation and transport. The chemistry in such models may include some 150 elementary chemical reactions and photochemical processes involving some 50 different species. Laboratory measurements of the rates of these reactions have progressed rapidly over the past decade and have given us a basic understanding of the kinetics of these elementary processes and the way they act in controlling ozone. This applies particularly in the upper stratosphere where local chemical composition is predominantly photochemically controlled.

It has proved more difficult to describe adequately both the chemistry and the dynamics in the lower stratosphere. Here the chemistry is complicated by the involvement of temporary reservoir species such as $HOCl$, $H_2O_2$, $HNO_3$, $HC_1$, $HNO_4$, $N_2O_5$ and $ClONO_2$ which 'store' active radicals and which strongly couple the $HO_x$, $NO_x$ and $ClO_x$ families. The long photochemical and thermal lifetimes of ozone and the reservoir species in this region give rise to strong interaction between chemistry and dynamics (transport) in the control of the distribution of ozone and other trace gases. Moreover, seasonal variability and natural perturbations due to volcanic injections of gases and aerosol particles add further to complicate the description and interpretation of atmospheric behavior in this region. Most of the changes in the predicted effects of chlorofluoromethanes and other pollutants on ozone column density have resulted from changes in our view of the chemistry in the lower stratosphere. A great deal of importance must therefore be attached to achieving an understanding of the key factors in ozone chemistry in this region of the atmosphere.

Description of atmospheric chemistry in the troposphere is similarly complicated by dynamical influence and additionally by the involvement of the precipitation elements (i.e. cloud, rain and snow) in the chemical pathways. The homogeneous chemistry of the troposphere is centered round the role of the hydroxyl radical in promoting oxidation and scavenging of trace gases released from surface terrestrial sources. Tropospheric OH is an important issue for stratospheric ozone since it controls the flux of source gases such as $CH_4$, halogenated hydrocarbons, and sulfur compounds to the stratosphere. Although the mechanisms are more complex due to the involvement of larger and more varied entities, the overall pattern of relatively rapid photochemical cycles involving a coupled carbon/hydrogen/nitrogen and oxygen chemistry is similar to that in the stratosphere. The photochemical cycles influence both the odd hydrogen budget and also, through coupling of the hydrocarbon oxidation with $NO_2$ photochemistry, the in situ production and removal of tropospheric ozone. The concentration and distribution of tropospheric ozone is important in respect of its significant contribution to the total ozone column, and its radiative properties in the atmospheric heat balance.

# Notes

1. United Nations Environment Program, *Vienna Convention for the Protection of the Ozone Layer, Final Act*, (Nairobi: UNEP, 1985). For further discussion, see pp. 21-22.

2. 42 U.S.C. § 7457 (Section 157). For an analysis of this law, see T. Stoel, A. Miller, and B. Milroy, *Fluorocarbon Regulation: An International Comparison* (Lexington, MA: Lexington, 1980)

3. *Federal Register*, Vol. 51, No. 7 (January 10, 1986) pp. 1257-60.

4. J. Farman, B. Gardiner, and J. Shanklin, "Large Losses of Total Ozone in Antarctica Reveal Seasonal $ClO_xIN_x$ Interaction," *Nature*, 1985, Vol. 315, pp. 207-210.

5. The proceedings of the conference are being published in four volumes. *See* J. Titus, ed., *Effects of Changes in Stratospheric Ozone and Global Climate* (Washington: EPA, 1986).

6. National Aeronautics and Space Administration, *Present State of Knowledge of the Upper Atmosphere, An Assessment Report*, NASA Reference Publication 1162 (Washington: NASA, 1986).

7. *Ibid*, ch. 12.

8. M. Molina and F.S. Rowland, "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone," *Nature*, 1974, Vol. 249, No. 5460: 810-12.

9. For a recent state-of-the-art review of scientific knowledge of processes controlling stratospheric ozone, see NASA *Assessment Report*. This report is based on a three-volume review titled *Atmospheric Ozone: Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change* (1985) prepared under the auspices of NASA, the World Meteorological Organization (WMO), and several other national and international scientific organizations.

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42. EEC, "Code of Good Practice." According to a Rand Corporation study, very few incinerators will accept fluorinated chemicals because they corrode the refractory lining materials, and those that do accept such chemicals charge dearly. Hammit et al., *Product Uses*, 60–61.

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