

# **Future Emission Scenarios for Chemicals That May Deplete Stratospheric Ozone**

James K. Hammitt, Frank Camm, Peter S. Connell, William E. Mouz,  
Kathleen A. Wolf, Donald J. Wuebbles, Anil Bamezai

*40 Years*  
1948-1988

**RAND**

Preparation of this report was supported by The RAND Corporation as part of its program of public service. Publication of the report was funded by a grant from the John M. Olin Foundation.

ISBN: 0-8330-0884-6

This Report contains an offprint of RAND research originally published in a journal or book. The text is reproduced here, with permission of the original publisher.

The RAND Publication Series: The Report is the principal publication documenting and transmitting RAND's major research findings and final research results. The RAND Note reports other outputs of sponsored research for general distribution. Publications of The RAND Corporation do not necessarily reflect the opinions or policies of the sponsors of RAND research.

Published by The RAND Corporation  
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90406-2138

R-3628-JMO/RC

# **Future Emission Scenarios for Chemicals That May Deplete Stratospheric Ozone**

James K. Hammitt, Frank Camm, Peter S. Connell, William E. Mooz,  
Kathleen A. Wolf, Donald J. Wuebbles, Anil Bamezai

March 1988

*40 Years*  
1948-1988

**RAND**



## PREFACE

This report is the product of a collaboration between researchers at The RAND Corporation and Lawrence Livermore National Laboratory. It is one of a series of RAND papers on policy issues associated with potential ozone depletion and builds from earlier RAND work. The paper was originally published in *Nature*, Vol. 330, December 24/31, 1987, pp. 711-716, and is reprinted in this format to facilitate distribution.

The report describes a set of subjective-probability-based scenarios for future emissions of the seven most important potential ozone-depleting substances, and the corresponding calculated ozone depletion, through the year 2040. The emission scenarios reflect uncertainty about future global economic growth and use of the seven chemicals in important industrial processes and consumer products, but assume no additional regulation on their use beyond that existing in 1987. In particular, the effects of any emission regulations that follow the September 1987 "Montreal Protocol on Substances That Deplete the Ozone Layer" are not incorporated. These scenarios describe a baseline against which the effects of proposed regulations can be compared.

Stratospheric ozone is important because it helps shield the earth from harmful ultraviolet radiation. Increases in ultraviolet radiation could threaten human health, reduce crop yields, speed deterioration of certain materials, and have a wide range of other potentially disruptive ecological effects. Atmospheric models developed and tested over the last decade, including the Lawrence Livermore National Laboratory model used here, suggest that global human emissions of potential ozone depleters may promote chemical reactions that reduce stratospheric ozone, thereby increasing ultraviolet radiation with its concomitant effects. Substantial scientific uncertainty persists about whether human emissions of these chemicals actually threaten stratospheric-ozone concentrations and, if they do, the extent to which lower ozone levels actually threaten human health and other activities in the biosphere. But policymakers must act in the face of this uncertainty, and RAND's work is designed to provide them with the best information available.

To that end, The RAND Corporation is developing a series of reports to aid analysts and policymakers responsible for policy decisions on emissions of potential ozone depleters worldwide. These documents report the results of research that includes extensive literature reviews, interviews with knowledgeable officials associated with the production and use of potential ozone depleters, and formal chemical, cost, economic, and statistical analyses. The series should also interest the much broader audience of analysts and decisionmakers whose organizations would be affected by government policies with respect to emissions of such chemicals.

Published papers in the series include the following:

- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications*, R-2524-EPA, June 1980.
- W. E. Mooz and T. H. Quinn, *Flexible Urethane Foams and Chlorofluorocarbon Emissions*, N-1472-EPA, June 1980.
- A. R. Palmer, W. E. Mooz, T. H. Quinn, and K. A. Wolf, *Economic Implications of Regulating Nonaerosol Chlorofluorocarbon Emissions: An Executive Briefing*, R-2575-EPA, July 1980.

- K. A. Wolf, *Regulating Chlorofluorocarbon Emissions: Effects on Chemical Production*, N-1483-EPA, August 1980.
- A. R. Palmer and T. H. Quinn, *Economic Impact Assessment of a Chlorofluorocarbon Production Cap*, N-1656-EPA, February 1981.
- A. R. Palmer and T. H. Quinn, *Allocating Chlorofluorocarbon Permits: Who Gains, Who Loses, and What Is the Cost?* R-2806-EPA, July 1981.
- W. E. Mooz, S. H. Dole, D. L. Jaquette, W. H. Krase, P. F. Morrison, S. L. Salem, R. G. Salter, and K. A. Wolf, *Technical Options for Reducing Chlorofluorocarbon Emissions*, R-2879-EPA, March 1982.
- E. M. Sloss and T. P. Rose, *Possible Health Effects of Increased Exposure to Ultraviolet Radiation*, N-2330-EPA, July 1985.
- T. H. Quinn, K. A. Wolf, W. E. Mooz, J. K. Hammitt, T. W. Chesnutt, and S. Sarma, *Projected Use, Emissions, and Banks of Potential Ozone-Depleting Substances*, N-2282-EPA, January 1986.
- F. Camm and J. K. Hammitt, *An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution*, N-2442-EPA, May 1986.
- F. Camm, T. H. Quinn, A. Bamezai, J. K. Hammitt, M. Meltzer, W. E. Mooz, and K. A. Wolf, *Social Cost of Technical Control Options To Reduce the Use of Potential Ozone Depleters in the United States: An Update*, N-2440-EPA, May 1986.
- J. K. Hammitt, K. A. Wolf, F. Camm, W. E. Mooz, T. H. Quinn, and A. Bamezai, *Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000*, R-3386-EPA, May 1986.
- W. E. Mooz, K. A. Wolf, and F. Camm, *Potential Constraints on Cumulative Global Production of Chlorofluorocarbons*, R-3400-EPA, May 1986.
- D. F. Kohler, J. G. Haaga, and F. Camm, *Projections of Consumption of Products Using Chlorofluorocarbons in Developing Countries*, N-2458-EPA, January 1987.
- B. M. Mitchell and J. R. Vernon, *The Health Costs of Skin Cancer Caused by Ultraviolet Radiation*, N-2538-EPA, February 1987.
- J. K. Hammitt, *Timing Regulations to Prevent Stratospheric-Ozone Depletion*, R-3495-JMO/RC, April 1987.

Preparation of this report was supported by The RAND Corporation, as part of its program of public service, using funds earned from its endowment and fee income. It builds from work at RAND funded by the U.S. Environmental Protection Agency, and at Lawrence Livermore National Laboratory under the auspices of the U.S. Department of Energy. Publication of the report was funded by a grant from the John M. Olin Foundation. The opinions and conclusions expressed are the authors' and do not necessarily reflect the views of the sponsoring organizations.

# Future emission scenarios for chemicals that may deplete stratospheric ozone

James K. Hammitt\*, Frank Camm\*, Peter S. Connell†, William E. Mooz\*, Kathleen A. Wolf\*, Donald J. Wuebbles† & Anil Bamezai\*

\* The RAND Corporation, 1700 Main Street, Santa Monica, California 90406-2138, USA

† Lawrence Livermore National Laboratory, PO Box 808, Livermore, California 94550, USA

*Scenarios are developed for long-term future emissions of seven of the most important manmade chemicals that may deplete ozone and the corresponding effect on stratospheric ozone concentrations is calculated using a one-dimensional atmospheric model. The scenarios are based on detailed analysis of the markets for products that use these chemicals and span a central 90% probability interval for the chemicals' joint effect on calculated ozone abundance, assuming no additional regulations.*

ENVIRONMENTALLY persistent halocarbons containing chlorine or bromine may reduce the concentration of stratospheric ozone<sup>1-4</sup> and contribute to global warming<sup>5</sup>. Industrially produced halocarbons that are believed to be among the most potent and are emitted in significant quantities include chlorofluorocarbons (CFCs) 11, 12 and 113, carbon tetrachloride, methyl chloroform and halons 1211 and 1301. Collectively, we call these substances 'potential ozone depleters' (PODs).

To date, most research on stratospheric ozone depletion has focused on reducing uncertainty about atmospheric photochemistry and physics. With a few exceptions<sup>4,6</sup>, most of the reported research has assumed no future growth in POD emissions. This has been appropriate for testing and comparing atmospheric models, but as policymakers rely on these models, a more realistic treatment of emissions and related uncertainties is becoming increasingly important. Here we describe a way for projecting future POD emissions and report what we believe to be a reasonable range of future emission scenarios, assuming

no additional emission regulations. Such estimates can be used to gauge the importance of current uncertainty about future emission profiles in assessing the likely extent of future ozone depletion and compare it with other sources of uncertainty. In addition, they are a necessary first step in assessing whether additional regulations are appropriate. Technologies for reducing POD emissions and their costs have been analysed elsewhere<sup>7-10</sup>.

The emission scenarios are developed using the four-step process described below. They span a subjective 90% probability region for the model-calculated joint effect of the seven PODs on globally averaged stratospheric ozone abundance until 2040<sup>11</sup>. (Unlike a confidence interval, a probability region describes an interval that one believes contains the unknown value of a variable with specified probability. It relies on bayesian as opposed to sampling theory.) The associated change in column ozone, as calculated using the Lawrence Livermore National Laboratory (LLNL) one-dimensional model, ranges between -1.8% and -17.3% in 2040. A subjective probability bound on future ozone depletion also requires analysis of uncertainty about other factors including the model specification, emissions of other trace gases and future social responses to perceived environmental risks.

PODs differ in the effectiveness with which a unit mass of each destroys ozone because of differences in molecular weight, the number of chlorine or bromine atoms per molecule, and the compounds' atmospheric lifetimes. The relative depletion efficiencies are estimated using the LLNL one-dimensional model. Table 1 illustrates one measure of their relative contributions to ozone depletion, expressed as the estimated share of current emissions weighted by the model-calculated depletion efficiency per unit mass. Other PODs (including CFC-22, 114 and 115) are quantitatively unimportant at current emission rates.

## Individual chemical projections

**Step 1.** Initially we develop base projections and ranges of uncertainty for POD use in various applications and regions. These projections represent a consensus of the RAND authors. They are developed from preliminary scenarios for each market that consider trends in the product market and in POD use per unit product, as well as factors that historically have influenced them or may in the future influence them. Preliminary illustrating the range of reasonably foreseeable results were constructed and interpreted as bounding an 80% probability region. These rely on detailed information about specific POD applications obtained through literature review and contact with over 500 industry officials since 1978<sup>7-9,12-14</sup>

**Table 1** Estimated relative contributions to ozone depletion

Chemical	Atmospheric lifetime (yr)*	Estimated global 1985 emissions (thousand tonnes)	Relative depletion efficiency*	Share of total contribution (%)
CFC-11 (CCl <sub>3</sub> F)	76.5	238	1.00	25.8
CFC-12 (CCl <sub>2</sub> F <sub>2</sub> )	138.8	412	1.00	44.7
Carbon tetrachloride (CCl <sub>4</sub> )	67.1	66	1.06	7.6
CFC-113 (CFCl <sub>2</sub> CF <sub>2</sub> Cl)	91.7	138	0.78	11.7
Methyl chloroform (CH <sub>3</sub> CCl <sub>3</sub> )	8.3	474	0.10	5.1
Halon 1301 (CF <sub>3</sub> Br)	100.9	3	11.4	3.7
Halon 1211 (CF <sub>2</sub> ClBr)	12.5	3	2.70	0.9
CFC-22 (CHF <sub>2</sub> Cl)	22.0	72	0.05	0.4

Atmospheric lifetime = steady-state atmospheric burden/constant emission rate. Relative depletion efficiency = O<sub>3</sub> depletion per unit mass of species/O<sub>3</sub> depletion per unit mass of CFC-11. Share of total contribution = 100 × S<sub>i</sub>/ΣS<sub>i</sub> where S<sub>i</sub> = 1985 emissions × relative depletion efficiency. Shares do not sum to 100 due to rounding.

\* Calculated using LLNL one-dimensional model.

Because of differences in available information, we distinguish between three world regions: the United States, the other countries whose CFC-11 and 12 production are reported by the Chemical Manufacturers Association<sup>15</sup> (the other OECD nations and most developing countries) and the non-reporting countries (primarily the USSR, China and Eastern Europe). The three regions respectively account for an estimated 30%, 56% and 14% of current world production, weighted by relative depletion efficiencies. For the period before 2000, we develop separate projections and uncertainty ranges for each of the major POD applications in the first two regions and for total use of each POD in the non-reporting countries<sup>12</sup>.

Such detailed analysis would become too speculative after 2000, so a more aggregate approach is used. Global use of most PODs is expected to grow with the global economy, and the uncertainty ranges reflect our uncertainty about the distant future relative to the period before 2000. The distribution for global economic growth is based on subjective probability distributions for global labour productivity and population developed by W. Nordhaus and G. Yohe (personal communication).

### Subjective probability distribution

**Step 2.** Step 1 produces a range of potential growth for each chemical during the periods 1985–2000 and 2000–2040. In the second step, we partition this growth into two components corresponding to growth in general economic activity and chemical use relative to this growth, then we integrate across regions and product applications to obtain components describing the growth of gross global product (GGP) and global POD use relative to GGP. This allows us to account for the correlation between chemicals that results because each is correlated with general economic activity. The distribution of these components is described by a subjective multivariate normal probability distribution, the parameters of which are summarized in Table 2. We assume the growth rates for chemical use relative to economic growth are independent of one another and of general economic growth, although correlations could be integrated using this methodology.

Standard deviations are smaller after 2000 because the length of the second period reduces the variance of the mean growth rates relative to those in the first period despite higher uncertainty about the annual growth rates. The annual variance is 25% greater for each chemical after 2000 than before<sup>11</sup>.

To understand better the considerations underlying the base projections, uncertainty ranges and corresponding probability distributions, consider the historical, economic, technological and regulatory factors associated with the use of each POD (for more detail, see ref. 12). Except for the sharp decline in aerosol use of CFC-11 and 12 (and in carbon tetrachloride used to produce these CFCs) that accompanied the ban on CFC use in aerosol products in the United States and other countries in the late 1970s, the available data suggest that growth in all seven PODs has been strong<sup>12,14,15</sup>.

CFC-11 and 12 growth in foam manufacture and most other applications is expected to continue, but use in aerosol and some refrigeration applications should stagnate or decline. In part, because these chemicals have been in use for many decades, substantial new applications are not expected. Slower growth could result if CFC-11 and 12 are displaced from current applications (certain foam uses, for example). Higher growth could reflect longer market-expansion periods in the developing nations or the emergence of major new markets.

Carbon tetrachloride is used primarily to produce CFC-11 and 12. Solvent and fumigant uses have been discontinued in the United States because of concerns about health effects, but may continue elsewhere. Future use is linked to CFC-11 and 12 production.

CFC-113 production has expanded dramatically in recent years, largely because of its widespread use as a solvent in the electronics industry. The base projection assumes continuing

**Table 2** Parameters of the subjective normal probability distribution for gross global product and chemical use relative to GGP

Chemical use relative to GGP	1985–2000		2000–2040	
	Mean	Standard deviation	Mean	Standard deviation
CFC-11	0.02	0.98	0	0.67
CFC-12	–1.00	1.05	0	0.72
Carbon tetrachloride	–0.49	1.02	0	0.70
CFC-113	3.27	1.67	0	1.15
Methyl chloroform	–0.32	1.10	0	0.75
Halon 1301	1.08	2.29	–0.45	1.57
Halon 1211	0.96	2.33	–0.05	1.60
Gross global product	3.28	1.15	2.40	0.96

Chemical growth rates are sum of growth rates of GGP and chemical use relative to GGP. Correlations among rates are zero. (Average growth rates in % per annum).

**Table 3** Production growth rates for joint distribution scenarios

Chemical	Period	Quantile of the score function				
		0.05	0.25	0.50	0.75	0.95
CFC-11	Pre-2000	1.47	2.54	3.29	4.03	5.12
	Post-2000	0.93	1.80	2.40	3.00	3.86
CFC-12	Pre-2000	0.39	1.50	2.27	3.04	4.15
	Post-2000	0.89	1.78	2.40	3.02	3.91
Carbon tetrachloride	Pre-2000	0.93	2.03	2.79	3.55	4.64
	Post-2000	0.91	1.79	2.40	3.01	3.89
CFC-113	Pre-2000	4.15	5.56	6.55	7.54	8.97
	Post-2000	0.51	1.63	2.40	3.18	4.29
Methyl chloroform	Pre-2000	1.03	2.17	2.96	3.74	4.88
	Post-2000	0.86	1.77	2.40	3.03	3.94
Halon 1301	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	–0.20	1.07	2.00	2.92	4.22
Halon 1211	Pre-2000	1.12	2.94	4.07	5.34	7.15
	Post-2000	0.19	1.51	2.47	3.39	4.72

Growth rates in % per annum.

high growth, although the 1986 US ban on land disposal of chlorinated solvents could moderate US growth by increasing disposal costs. Higher growth could occur if competing solvents (such as trichloroethylene, perchloroethylene and methylene chloride) face additional regulations.

Methyl chloroform is used largely in solvent and adhesive applications. As for CFC-113, growth may be affected by substitution among solvents stimulated by the land-disposal ban or more stringent regulation of other chlorinated solvents. Because methyl chloroform is a mature chemical with well-established applications, growth should approximate that of GGP.

Halon 1301 has been rapidly adopted for use as a fire extinguishant in enclosed spaces such as computer rooms. Growth depends on the number and size of new systems and on whether the chemical is recovered and reused when systems are dismantled.

Halon 1211 is increasingly used in portable fire extinguishers. Recovery is unlikely because of the small quantities in individual units.

### Joint production scenarios

**Step 3.** Production growth rates for individual chemicals are correlated with GGP growth, but not perfectly. Thus, it would be incorrect to combine production growth rates corresponding to the 95th percentiles of the distributions for each chemical and call this a '95th percentile' joint scenario: such an approach would lead to a larger model-calculated effect on ozone than is associated with the 95th percentile of our joint distribution.



**Table 4** Production and (emissions) for joint distribution scenarios

Chemical and year	Quantile of the score function				
	0.05	0.25	0.50	0.75	0.95
<b>CFC-11</b>					
1985	342 (238)	342 (238)	342 (238)	342 (238)	342 (238)
2000	426 (309)	499 (358)	556 (396)	619 (438)	723 (507)
2040	618 (525)	1,017 (819)	1,435 (1,122)	2,022 (1,543)	3,294 (2,445)
<b>CFC-12</b>					
1985	444 (412)	444 (412)	444 (412)	444 (412)	444 (412)
2000	471 (467)	555 (541)	622 (599)	696 (662)	817 (765)
2040	672 (662)	1,125 (1,092)	1,606 (1,544)	2,287 (2,178)	3,788 (3,559)
<b>Carbon tetrachloride</b>					
1985	1,029 (66)	1,029 (66)	1,029 (66)	1,029 (66)	1,029 (66)
2000	1,183 (76)	1,391 (90)	1,554 (100)	1,736 (112)	2,032 (131)
2040	1,702 (110)	2,827 (182)	4,014 (259)	5,686 (366)	9,339 (601)
<b>CFC-113</b>					
1985	163 (138)	163 (138)	163 (138)	163 (138)	163 (138)
2000	300 (253)	367 (310)	423 (357)	485 (410)	591 (499)
2040	367 (310)	700 (591)	1,091 (922)	1,695 (1,432)	3,172 (2,680)
<b>Methyl chloroform</b>					
1985	545 (474)	545 (474)	545 (474)	545 (474)	545 (474)
2000	636 (554)	752 (654)	844 (734)	946 (823)	1,113 (969)
2040	898 (781)	1,517 (1,320)	2,179 (1,896)	3,123 (2,717)	5,215 (4,537)
<b>Halon 1301</b>					
1985	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)
2000	13.6 (5.6)	16.7 (6.5)	19.4 (7.1)	22.4 (7.9)	27.7 (9.2)
2040	9.9 (8.5)	24.2 (14.7)	43.2 (22.0)	75.4 (33.6)	163 (62.9)
<b>Halon 1211</b>					
1985	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)	10.7 (3.0)
2000	13.6 (5.6)	16.7 (6.5)	19.4 (7.1)	22.4 (7.9)	27.7 (9.2)
2040	17.5 (16.1)	34.1 (24.6)	55.1 (33.9)	89.6 (47.9)	182 (81.3)

Units are thousand tonnes.

The joint scenarios are derived from a 'score function' consisting of a weighted sum of the growth rates for each chemical. The weights reflect the compounds' capabilities to deplete ozone, based on each chemical's share of total production weighted by the fraction that is eventually emitted and its relative depletion efficiency. The weights change over time because of shifts in relative production, but begin with values similar to those in the last column of Table 1. (Because relative depletion efficiencies for the halons were not available, we used approximate efficiencies of 10.0 for both halons, 0.1 for methyl chloroform, and 1.0 for the other four PODs<sup>11</sup>.)

The score function provides a rough measure of the potential effectiveness of these chemicals, taken together, in depleting stratospheric ozone. Moreover, we can derive a probability distribution for its value using the subjective probability distribution for individual chemical growth rates.

Scenarios are defined by quantiles of the score function's distribution. For example, the '95th percentile' scenario is constructed so the subjective probability that the value of the score function will be higher is 5%. Each value of the score function is associated with an infinite number of combinations of individual-chemical growth rates. We choose the unique set for which all of the GGP and chemical use components correspond to a common quantile of their respective marginal distributions. This choice distributes responsibility for the joint effect across all seven PODs: it associates relatively high- or low-growth scenarios for individual chemicals together.

Table 3 reports the production growth rates for various scenarios, and Table 4 presents the corresponding production levels. The procedure significantly narrows the range of scenarios, compared with an approach that does not adjust for joint variation. For example, the 95th percentile scenario uses growth rates drawn from the 82nd percentile of the distributions for individual chemicals. Analogously, the growth rates associated with low scenarios are raised.

## Emission scenarios

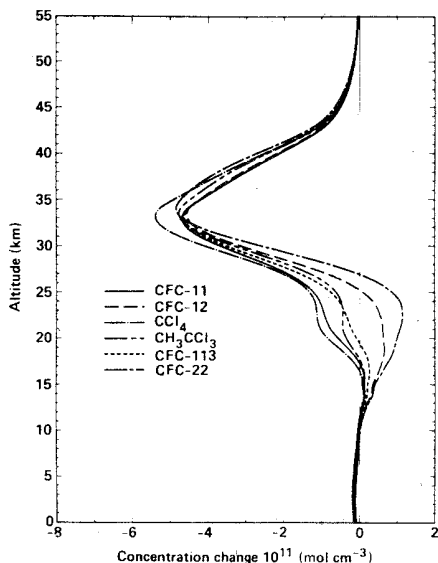
**Step 4.** The timing of POD emissions varies by application. In some, PODs are released to the atmosphere shortly after manufacture. In others, they remain 'banked' in products until disposal. The last step introduces appropriate lags between production and emission for each POD. Resulting emissions are reported in Table 4.

CFC-11 and 12 applications can be divided into five categories. (1) Hermetically sealed applications (home refrigerators and freezers) have estimated typical lifetimes of 17 years during which small amounts of CFC-12 are emitted as individual units fail. (2) Non-hermetically sealed applications (retail-food refrigerators, building chillers, mobile air conditioners) lose CFCs through leakage and servicing throughout their lives, estimated to be seven years. (3) Urethane closed-cell foams emit CFC-11 very slowly. During their estimated 30-year service lives, emissions decline geometrically and are characterized by an assumed 100-year half life (based on measurements by Khalil and Rasmussen<sup>16</sup>). After disposal, emissions are assumed to accelerate to reflect the breakup of the foam into smaller pieces. Additional small amounts are emitted at manufacture. (4) Non-urethane foams release CFC-12 over an estimated two-year period. (5) Prompt emitters (aerosol propellants, flexible-foam blowing, sterilants) emit CFCs as they are used, shortly after manufacture.

Approximately 94% of carbon tetrachloride produced is used as an intermediate in the manufacture of CFCs. Most of the remainder is emitted promptly.

Most CFC-113 and methyl chloroform emissions are immediate, although an estimated 15% of production is lost in waste-disposal dumps, incinerated, or used as intermediates in manufacturing other chemicals.

Halons are largely banked in fire-extinguishing systems that have estimated service lives of up to 40 years. Small amounts



**Fig. 1** Vertical profiles of calculated ozone concentration change for fixed emissions of six Cl-containing PODs at steady state. Surface POD emissions were normalized to produce the same abundance of inorganic Cl-containing species at 35 km in each case.

are emitted annually through leakage, fire, and inadvertent discharge, and at disposal.

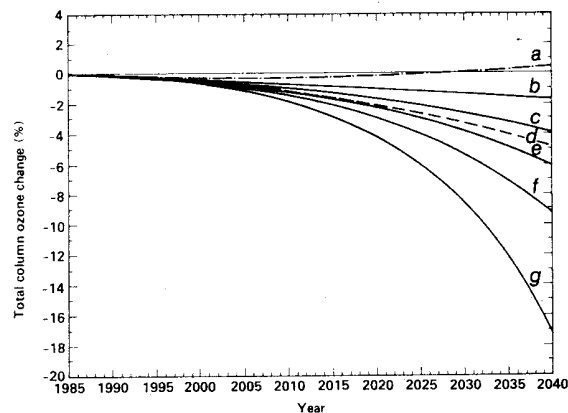
### Atmospheric model calculations

The joint emission scenarios provide boundary conditions for the LLNL one-dimensional model of transport, photochemical kinetics and radiative processes in the troposphere and stratosphere. The model is representative of those used for calculating future ozone changes and has been described previously<sup>6,17,18</sup>. Its domain extends from the Earth's surface to 55 km, and it includes 165 photolytic and thermal reactions of 52 chemical species, a diffusive representation of globally averaged transport, and interactive calculation of the temperature profile above 14 km (assuming radiative equilibrium). All significant known homogeneous photochemistry of the oxygen, nitrogen oxide, chlorine, bromine and methane families is included. Kinetic rate constants and photochemical parameters are based on the recommendations of the NASA Panel for Data Evaluation<sup>19</sup>. From an initial condition representing the current (1985) atmosphere, integration over time produces the model-predicted global annual average changes in tropospheric and stratospheric ozone abundances. We also use the model to calculate relative depletion efficiencies for the seven PODs to compare with those used in developing the joint scenarios.

The calculated change in total column ozone represents an annual global average of the seasonally and latitudinally varying changes that are expected to result from POD and other trace gas emissions. One-dimensional model results are useful for delineating the ranges of calculated ozone change that arise from uncertainties about future POD emissions and other factors, although higher-dimensional models are preferred for estimating effects on the biosphere.

### Model-calculated relative depletion efficiencies

Relative ozone-depletion efficiencies play an important role in constructing the score function above. They can be calculated using the one-dimensional model by comparing total column ozone change calculated at steady state for a specified emission of a particular POD to that calculated for any reference POD; we used CFC-11. At steady state, the surface emission and atmospheric destruction of the POD are balanced, and an equilibrium vertical profile of the POD abundance is established. The model-calculated atmospheric lifetime is equal to the ratio of



**Fig. 2** Calculated one-dimensional total column ozone change for seven POD emission scenarios. Assumed growth rates for other trace gases are consistent with current trends: CO<sub>2</sub>, 0.64% per yr; N<sub>2</sub>O, 0.25% per yr; CH<sub>4</sub>, 1% per yr; CFC-22, 0% per yr. a, Constant future POD emissions; b, 0.05 quantile of score function; c, 0.25 quantile of score function; d, 0.50 quantile of score function with CFC-11, 12 production cap; e, 0.50 quantile of score function; f, 0.75 quantile of score function; g, 0.95 quantile of score function.

the steady-state atmospheric burden to the prescribed emission rate.

In determining relative efficiencies, emission levels were chosen to produce similar calculated total column ozone depletions for each species to minimize differences caused by other effects such as the 'self-healing' increase in lower stratospheric ozone when upper stratospheric ozone is depleted. Specified surface emissions for each POD were integrated over a period of about three POD-dependent atmospheric lifetimes. The calculated relative efficiencies by emitted mass and atmospheric lifetimes are reported in Table 1.

Because the active agent in POD-caused ozone depletion is the chlorine or bromine released in the stratosphere, relative efficiencies by mass depend on the parent molecule's molecular weight, number of chlorine and bromine atoms, and atmospheric lifetime. These factors account for most of the variation in relative efficiency. Figure 1 shows that the ozone-depletion profiles for CFC emissions normalized for differences in these factors are roughly equivalent. Some of the remaining spread can be related to the vertical profiles of atomic chlorine release by photolysis of the CFCs. CFC-22 and 12 appear slightly less efficient in decreasing the total column ozone on this normalized basis because they have higher average altitudes for photolysis, and thus contribute less chlorine to the lower stratosphere than the other compounds. Smaller chlorine abundances in the lower stratosphere are currently thought to increase ozone abundances locally as a result of interactions with the dominant ozone-loss processes, the reactions of the nitrogen oxides.

### Model-calculated ozone depletion

To calculate the predicted effects on ozone of the joint POD emission scenarios, trends for other atmospheric trace species must be assumed. The ambient 1985 atmosphere is obtained using industrial emission estimates for the CFCs and observed trends for CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> abundances as boundary conditions<sup>17</sup>. For future growth in trace gas abundances we use the CO<sub>2</sub> projection in Edmonds *et al.*<sup>20</sup> (averaging 0.64% per yr) and assume continuation of currently estimated global average trends in N<sub>2</sub>O (0.25% per yr) and CH<sub>4</sub> (1% per yr)<sup>18</sup>. Surface emissions of CFC-22 are fixed at the current rate of ~71.9 thousand tonnes per yr. The effects of uncertainties in these assumptions on calculated ozone change are discussed by Connell and Wuebbles<sup>17</sup>.

Figure 2 shows changes in model-calculated total column

Table 5 Calculated surface abundances for joint emission scenarios

Chemical	Year	Zero emission growth	Quantile of the score function					0.50 with production cap
			0.05	0.25	0.50	0.75	0.95	
Parts per billion								
CFC-11	1985	0.206	0.206	0.206	0.206	0.206	0.206	0.206
	2000	0.300	0.332	0.346	0.356	0.367	0.385	0.356
	2040	0.508	0.770	0.995	1.21	1.48	2.01	0.860
CFC-12	1985	0.377	0.377	0.377	0.377	0.377	0.377	0.377
	2000	0.626	0.653	0.676	0.694	0.713	0.742	0.694
	2040	1.18	1.46	1.87	2.27	2.77	3.77	1.66
Carbon tetrachloride	1985	0.153	0.153	0.153	0.153	0.153	0.153	0.153
	2000	0.158	0.161	0.164	0.167	0.169	0.174	0.167
	2040	0.166	0.199	0.249	0.297	0.358	0.480	0.297
CFC-113	1985	0.033	0.033	0.033	0.033	0.033	0.033	0.033
	2000	0.089	0.113	0.124	0.132	0.141	0.156	0.132
	2040	0.199	0.364	0.538	0.718	0.967	1.51	0.718
Methyl chloroform	1985	0.138	0.138	0.138	0.138	0.138	0.138	0.138
	2000	0.175	0.191	0.211	0.226	0.242	0.268	0.226
	2040	0.201	0.303	0.478	0.637	0.861	1.31	0.641
Parts per trillion								
Halon 1301	1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000	3.39	4.99	5.43	5.75	6.13	6.73	5.75
	2040	10.3	22.8	31.8	40.6	52.9	80.6	40.6
Halon 1211	1985	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2000	2.10	3.23	3.55	3.78	4.06	4.50	3.78
	2040	3.15	14.9	19.8	24.8	31.8	46.8	24.9
Other trace gases (all scenarios) parts per million								
	Year	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O				
	1985	345	1.74	0.303				
	2000	372	2.03	0.315				
	2040	490	3.02	0.348				

Quantities are given in moles of chemical per mole of atmosphere.

ozone for the joint emission scenarios. Also shown are the calculated changes resulting from constant POD emissions at 1985 rates, and from the 50th percentile scenario with a cap on CFC-11 and 12 production at the estimated current world capacity, 1.24 million tonnes<sup>21</sup>. Table 5 reports the corresponding calculated surface abundance of the seven PODs and other trace gases at selected dates.

The range of calculated ozone changes corresponding to the 5th and 95th percentile scenarios spans an order of magnitude (-1.8% to -17.3%) by 2040. At -6.2%, the 50th percentile scenario falls nearer the geometric than the arithmetic mean of the other scenarios, as the distribution of ozone depletion is skewed to the smaller depletion side. This skewness reflects the skewness of emission levels, resulting from the symmetry of growth rates across scenarios.

Even if POD emissions are held to 1985 levels, POD abundances continue to increase because of the long atmospheric lifetimes. The initial small decrease in column ozone abundance in this case is followed by a continuing small increase as CO<sub>2</sub> and CH<sub>4</sub> abundances increase. Increasing CO<sub>2</sub> cools the stratosphere and slows ozone-loss processes. Increasing CH<sub>4</sub> has the net effect of increasing ozone as a by-product of methane oxidation in the lower stratosphere and troposphere, and by sequestering active chlorine species in the inactive form of HCl.

Capping CFC-11 and 12 production at estimated current capacity in the 50th percentile scenario allows production of these species to increase until 2003, after which they remain constant. Ozone depletion continues, reaching -4.9% in 2040, about 1.3 percentage points less than under the uncapped scenario. Stratospheric inorganic chlorine abundances continue to increase because of increasing emissions from the bank, the CFCs' long atmospheric lifetimes, and increasing emissions of other PODs.

The range of calculated ozone depletion represents a subjective 90% probability interval for the calculated joint effect of the seven PODs on stratospheric ozone, assuming no additional regulations. It represents that part of our uncertainty about future depletion associated with current uncertainty about future uncontrolled POD emissions. A probability interval for future ozone depletion requires assessment of other factors that contribute to that uncertainty, including trends in abundances of other gases, the photochemical and kinetic processes modelled, and possible regulations.

## Conclusions

Uncertainty about future POD emissions is substantial. But because the compounds' growth rates are not perfectly correlated, uncertainty about their calculated joint effect on ozone is proportionally smaller than uncertainty about the calculated effect of any one of them. Moreover, it appears highly likely that this joint effect will continue to grow, assuming no additional regulations. The commonly used zero-emission-growth scenario falls below the 5th percentile of the distribution of the score function; even though emissions of some PODs may decline, we estimate a greater than 95% chance that total weighted emissions will increase.

A significant factor underlying this result is that almost all observers expect general economic growth to continue over the period analysed<sup>14</sup>. Our low-growth scenarios combine lower-than-expected economic growth with declining POD use relative to GGP. These low average rates are reasonable to expect only if major changes in regulation, product innovation, or other forces offset the general trend of global economic growth.

The emission levels shown in Table 4 suggest that CFC-11 and 12 will continue to be the chemicals most likely to contribute

to any ozone depletion that occurs, as they are at present. Such a conclusion, however, requires further analysis. The method used to construct scenarios groups low growth rates for individual chemicals together into low scenarios and high rates into high scenarios; this creates more stable shares than can reasonably be expected. Because the analysis focuses on total ozone depletion and not on the exact PODs that are responsible, this approach is appropriate. But it does not address the relative importance of each chemical.

Received 6 April; accepted 12 October 1987.

1. Molina, M. J. & Rowland, F. S. *Nature* **249**, 810-812 (1974).
2. Cicerone, R. J., Stolarski, R. S. & Walters, S. *Science* **185**, 1165-1167 (1974).
3. Stolarski, R. S. *Am. Stat.* **36**, 303-311 (1982).
4. Prather, M. J., McElroy, M. B. & Wofsy, S. C. *Nature* **312**, 227-231 (1984).
5. Dickinson, R. E. & Cicerone, R. J. *Nature* **319**, 109-115 (1986).
6. Wuebbles, D. J. *J. geophys. Res.* **88**, 1433-1443 (1983).
7. Palmer, A. R., Mooz, W. E., Quinn, T. H. & Wolf, K. A. *Economic Implications of Regulating Chlorofluorocarbon Emissions from Nonaerosol Applications* R-2524-EPA (The Rand Corporation, Santa Monica, 1980).
8. Mooz, W. E. *et al. Technical Options for Reducing Chlorofluorocarbon Emissions* R-2879-EPA (The Rand Corporation, Santa Monica, 1982).
9. Camm, F. *et al. Social Cost of Technical Control Options to Reduce Emissions of Potential Ozone Depleters in the United States: An Update* N-2440-EPA (The Rand Corporation, Santa Monica, 1986).
10. Hammitt, J. K. *Timing Regulations to Prevent Stratospheric-Ozone Depletion* R-3495-JMO/RC (The Rand Corporation, Santa Monica, 1987).
11. Camm, F. & Hammitt, J. K. *An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution* N-2442-EPA (The Rand Corporation, Santa Monica, 1986).
12. Hammitt, J. K. *et al. Product Uses and Market Trends for Potential Ozone-Depleting Substances 1985-2000* R-3386-EPA (The Rand Corporation, Santa Monica, 1986).
13. Kohler, D. F., Haaga, J. & Camm, F. *Projections of Consumption of Products Using Chlorofluorocarbons in Developing Countries* N-2458-EPA (The Rand Corporation, Santa Monica, 1987).
14. Quinn, T. H. *et al. Projected Use, Emissions and Banks of Potential Ozone Depleting Substances* N-2282-EPA (The Rand Corporation, Santa Monica, 1986).
15. Chemical Manufacturers Association *Production, Sales and Calculated Release of CFC-11 and CFC-12 through 1985* (Chemical Manufacturers Association, Washington DC, 1986).
16. Khalil, M. A. K. & Rasmussen, R. A. *J. Air Pollut. Control. Ass.* **36**, 159-163 (1986).
17. Connell, P. S. & Wuebbles, D. J. *Ozone Perturbations in the LLNL One-Dimensional Model—Calculated Effects of Projected Trends in CFCs, CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O, and Halons over 90 Years* UCRL-95548 (Lawrence Livermore National Laboratory, Livermore, 1986).
18. World Meteorological Organization *Atmospheric Ozone 1985: Assessment of Our Understanding of the Processes Controlling its Present Distribution and Change* Report No. 16 (Global Ozone Research and Monitoring Project, Washington DC, 1986).
19. DeMore, W. B. (ed.) *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling* Publication 85-37 (Jet Propulsion Laboratory, Pasadena, 1985).
20. Edmonds, J. A., Reilly, J., Trabalka, J. R. & Reichle, D. E. *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO<sub>2</sub>* Technical Report TR013 (US Department of Energy Carbon Dioxide Research Division, Washington DC, 1984).
21. Mooz, W. E., Wolf, K. A. & Camm, F. *Potential Constraints on Cumulative Global Production of Chlorofluorocarbons* R-3400-EPA (The Rand Corporation, Santa Monica, 1986).
22. Crawford, M. *Science* **237**, 1557 (1987).

We thank J. Acton for helpful comments. This work was performed, in part, under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory, and was supported by the US Environmental Protection Agency, the RAND Corporation and the John M. Olin Foundation.

*Note added in proof:* The results presented here do not reflect the recently concluded Montreal Protocol on Substances that Deplete the Ozone Layer<sup>22</sup>.







