INTERNATIONAL JOURNAL OF CLIMATOLOGY, VOL. 10, 439–450 (1990) 551.510.42:551.521.3:551.524.34

# THE CFC GREENHOUSE POTENTIAL OF SCENARIOS POSSIBLE UNDER THE MONTREAL PROTOCOL

WILFRID BACH and ATUL K. JAIN

*Center for Applied Climatology and Environmental Studies, Department of Geography, University of Münster, Robert-Koch-Str. 26, D-4400 Münster, FRG*

*Received 4 September 1989*
*Revised 31 January 1990*

## ABSTRACT

Measurement campaigns have given concrete evidence of serious ozone destruction both over the Antarctic and the Arctic regions. This has spawned international action for the protection of the ozone layer, such as the Vienna Convention in 1985 and the Montreal Protocol in 1987. Current chlorofluorocarbon (CFC) reduction plans are, however, inadequate. Therefore, a strengthening of the Protocol's provisions is intended for 1990. The urgency of the Protocol's revision gains strength by the fact that the ozone depleting CFCs have also a strong greenhouse potential, thereby contributing significantly to climatic change.

In this paper we consider five CFC production and emission scenarios (scenarios A–E) that are possible under the Protocol's provisions, and two phase-out scenarios by 2000 and 1996, respectively (scenarios F and G). The possible global mean surface temperature changes are calculated with the parameterized form of a one-dimensional radiative–convective model from 1986 to 2050 for the five CFCs (11, 12, 113, 114, and 115) controlled by the Protocol, eight additional CFCs, some of which could be used as possible substitutes, and the main greenhouse gases $CO_2$, $CH_4$, $N_2O$. The key findings are as follows. Without control, in 2050 the equilibrium global mean warming due to the five CFCs could rise sixteen fold above the 1985 value. The present Protocol provisions would still permit two to nine times higher equilibrium temperatures than today. A phase-out by 2000 and 1996 would, over the period of 1986–2050, result in a reduction from the present equilibrium temperature change of 9 and 18 per cent, respectively. In addition, the other CFCs (e.g. $CCl_4$, $CH_3CCl_3$, HFC-22) may add significantly to global warming and thus should also be controlled. The high greenhouse warming potential provides another strong motive for the necessity of a phase-out of all ozone-depleting CFCs.

KEY WORDS Montreal Protocol CFCs Trace gases Ozone depletion potential Greenhouse potential Climate protection

## OZONE DEPLETION POTENTIAL OF CHLOROFLUOROCARBONS

More than a decade ago attention was drawn to the accumulation in the stratosphere of industrially produced chlorofluorocarbons (CFCs), where they destroy the ozone shield that protects life on Earth from harmful UV-B radiation (Molina and Rowland, 1974; Stolarski and Cicerone, 1974). The original theory—long since verified—essentially states that the relatively stable CFC molecules survive unchanged on their way from the troposphere to the stratosphere, within which the ozone layer is situated. Under the influence of increased solar radiation, reactive chlorine is set free by photochemical action on CFCs. The natural ozone is reduced to molecular oxygen but the reactive chlorine atoms remain unchanged, thereby subjecting catalytically tens of thousands of additional ozone molecules to destruction.

Chlorine compounds differ significantly in their efficiency to destroy ozone. This relative ozone depletion potential (ODP) is usually assessed with the help of a one-dimensional photochemical model. The ODP values are not uncontroversial because they take into account only the total column ozone and not the vertical changes (see the detailed discussion in the report of the Enquete-Commission (1988)). Table I shows the ODP values for the CFCs controlled by the Montreal Protocol. It is, above all, the ozone depletion potential of the CFCs that has spawned international action.

0899–8418/90/050439–12$06.00

Table I. Characteristics of the CFCs to be controlled by the Montreal Protocol

| Compound | Production 1986 (kt) | Growth[c] rate (per cent year$^{-1}$) | Life time[d] (year) | Conversion factor (tonnes to ppbv) | Concentration[e] (ppbv) | Relative ozone depletion potential[g] | Relative greenhouse warming potential[h] |
|---|---|---|---|---|---|---|---|
| $CFCl_3$ (CFC-11) | 401·2[a] | 5·0 | 75[e] | $0·041 \times 10^{-6}$ | 0·234 | 1·0 | 0·87[d] |
| $CF_2Cl_2$ CFC-12 | 497·8[a] | 4·0 | 110 | $0·046 \times 10^{-6}$ | 0·395 | 1·0 | 1·00 |
| $C_2F_3Cl_3$ (CFC-113) | 157·8[b] | 4·0 | 90 | $0·032 \times 10^{-6}$ | 0·054[f] | 0·8 | 1·42[i] |
| $C_2F_4Cl_2$ (CFC-114) | 14·9[b] | 4·0 | 180 | $0·033 \times 10^{-6}$ | 0·020[f] | 1·0 | 1·64[i] |
| $C_2F_5Cl$ (CFC-115) | 4·9[b] | 4·0 | 380 | $0·037 \times 10^{-6}$ | 0·006[f] | 0·6 | 1·20[j] |

[a] Rand (1986).

[b] Environmental Protection Agency (1988a).

[c] CFC-11 and CFC-12 are assumed to grow at 1981–1984 rates (Wigley, 1988) while the others grow at current rates of 1985–1986 (Environmental Protection Agency, 1988b).

[d] Ramanathan *et al.* (1985).

[e] Wigley (1988).

[f] These concentrations are estimated by extrapolating the Ramanathan *et al.* (1985) values of 1980.

[g] United Nations Environment Programme (1987).

[h] All values are expressed on a per unit volume basis.

[i] The Rogers and Stephens (1988) values, which are on a per unit mass basis, are scaled to a per unit volume basis.

[j] Reijnders (1987).

## INTERNATIONAL ACTIVITIES FOR THE PROTECTION OF THE OZONE LAYER

In Vienna in 1985 the United Nations Environment Programme (UNEP) initiated a global framework convention for the protection of the ozone layer, which entered into force in 1988. Work in a series of technical workshops led to implementation plans as laid down in the Montreal Protocol. The framework, in its present form, was adopted in 1987, and it entered into force in February 1989. At that time 33 countries had ratified it.

It soon became clear from additional modelling efforts (e.g. those commissioned by the Enquete-Commission of the German Parliament) that the reduction plans as specified in the Montreal Protocol were insufficient. This and recent measurement series, which verified ozone destruction both over the Antarctic (Ozone Trends Panel Report, 1988) and the Arctic (Anon., 1989), initiated actions that will lead to a revision of the Montreal Protocol as early as 1990.

In February 1988 the Council of European Communities ruled unanimously to phase-out CFCs controlled by the Montreal Protocol by year 2000. This initiative was welcomed also by the USA and Canada. In March 1989 the 'London Conference on Saving the Ozone Layer' brought together 123 countries. At the Conference, 20 countries indicated that they hoped to sign the Protocol soon, raising the total number of parties to 53, and 12 countries promised to give it serious consideration. Developing countries (DCs) headed by China and India, while acknowledging the seriousness of the ozone depletion problem, made it quite clear that they would need substantial financial and technical aid to adopt a technology that will by-pass the ozone-destroying substances used today. At the May 1989 Helsinki meeting (see below), the Industrialized Countries (ICs) pledged to establish a special fund to help DCs in their economic development.

In April 1989, UNEP convened the first conference of contracting parties to the Vienna Convention. This was followed in May 1989, in Helsinki, by the first meeting of the contracting parties to the Montreal Protocol. The latter saw 102 delegations from 90 countries. The purpose of these meetings was the assessment of the scientific, environmental, economic, technical, and legal aspects to be considered in a revision of the Protocol. The timetable envisaged four reviews up to July 1989, the preparation of the revisions between August and October 1989, and, finally, the approval of the revision in the summer of 1990.

The urgency of controlling the ozone-depleting CFCs is underlined by the fact that they also have a noticeable greenhouse potential, thereby contributing significantly to global climatic change.

## GREENHOUSE POTENTIAL OF CFCs

Chlorofluorocarbons efficiently trap outgoing infra-red radiation from the Earth, thus contributing to the greenhouse warming of the Earth's surface (Ramanathan, 1975; Wang *et al.*, 1976; Dickinson and Cicerone, 1986). Although these compounds represent only a small fraction of the total atmospheric gases, many of the CFCs, such as CFC-11 and CFC-12, potentially play an important role in altering the global climate through the modification of the Earth's radiation balance. The contribution of the major anthropogenic constituents to greenhouse warming for the period 1880–1980 is 50, 19, 17, 8, 4, and 2 per cent for $CO_2$, $CH_4$, CFC-11 plus CFC-12, $O_3$, $N_2O$ in the troposphere, and $H_2O$ in the stratosphere, respectively (Ramanathan *et al.*, 1985). There is scientific consensus that, with the continuation of present trends, an unprecedented climatic change can be expected within the next two to eight decades or so, with potentially far-reaching impacts on ecosystems, food production, sea level, water and energy resources, etc. (Bach, 1984).

Table I lists the greenhouse warming potential of only those CFCs that come under the control of the Montreal Protocol. Other important CFCs that also contribute to greenhouse warming, such as $CCl_4$ (carbon tetrachloride), $CH_3CCl_3$ (methyl chloroform), and $CHClF_2$ (F-22), must also be taken into account (see Table V).

The main purpose of this paper is to examine the greenhouse warming due to future CFC concentration trends permitted under the Montreal Protocol (Table I). The greenhouse potential of the CFCs listed in Table V is also assessed. Some of these, such as $CHClF_2$ and $CH_3CCl_3$, have been considered as potential substitutes for CFCs in refrigeration and foam, respectively. There may be additional CFCs already in the atmosphere for which the greenhouse potential is not yet known, and there will be more CFCs from future production. All of these would have to be considered in an overall assessment of greenhouse potential.

## PRODUCTION SCENARIOS

The Montreal Protocol aims at reducing global CFC production to 50 per cent of the 1986 level in three steps: (i) a cut-back to 1986 production levels by mid-1989; (ii) a 20 per cent cut by mid-1993; and (iii) an additional 30 per cent reduction by mid-1999. Developing countries are allowed to delay compliance with the Protocol by 10 years beginning in 1989. Their production limits refer to either of the reference levels, either,

0·3 kg per capita or
the average production value for the period 1995–1997, whichever is lower.

In spite of its careful wording, the Protocol still permits a wide range of future productions, mainly due to the different exemptions granted to the ICs and the DCs. Industrialized countries are allowed to exceed the CFC production limit by 10 per cent between July 1989 and June 1998, and by a further 15 per cent thereafter. The DCs may increase the production/consumption level of controlled substances to 0·3 kg per capita during a 10-year period of grace beginning in 1989.

To obtain the 1986 world production data of CFCs, we have extrapolated the 1985 values (Rand, 1986; Environmental Protection Agency, 1988a) using the growth rates given in Table I. These estimates are in good agreement with those of the Office of Technology Assessment (1988) and Wigley (1988).

For this study we have constructed the following five scenarios, which, except for A, account for most of the possible uncertainties associated with the Montreal Protocol.

*Scenario A.* In this scenario the future world CFC production increases at the historical growth rates (Table I). This scenario is constructed to provide an upper bound.

*Scenario B.* All signatory countries producing two-thirds (67 per cent) of the world's production of CFCs (the minimum required for the Protocol to enter into force) ratify the Montreal Protocol and take advantage of all legally permitted exemptions as discussed above. To the 67 per cent, the ICs contribute 90 per cent and the DCs 10 per cent. The production of the remaining countries (non-signatory countries) grows at the growth rates given in Table I.

*Scenario C.* Same as scenario B but with signatory countries strictly following the Protocol (i.e. not taking advantage of the exemptions).

*Scenario D.* All countries (i.e. 90 per cent ICs and 10 per cent DCs) ratify the Montreal Protocol and take advantage of all legally permitted exemptions.

*Scenario E.* Same as scenario D with none of the countries taking advantage of the legally permitted exemptions.

In scenarios B–E, the production of CFCs is assumed to grow at the current growth rates from 1986 to 1989. For exemption scenarios B and D, it is assumed that the production of the DCs is increased to 0·3 kg per capita from 1989 to 1995 and stays constant over the period 1996–1998. For the non-exemption scenarios C and E, the production of the DCs grows at the current growth rates (Table I) during a 10-year period of grace (1989–1998).

These five scenarios represent the broad range that is possible under the present provisions of the Protocol. However, there is general consensus that they cannot adequately protect the world from severe ozone depletion because of the continued build-up of ozone-destroying chlorine in the stratosphere. Therefore, many countries envisage stricter CFC control than that laid down in the Protocol. For example:

(i) the Swedish Government has scheduled to phase-out currently regulated CFCs by 1995;

(ii) the Dutch Government is heading for a complete CFC phase-out by 2000;

(iii) the Federal Republic of Germany is planning to achieve a 95 per cent CFC reduction by 1996 compared with 1986. Accordingly, the existing Chemical Act is currently in the process of being amended;

(iv) the Environment Commissioner of the EC has proposed a complete phase-out by 1996, and this has been supported, especially by Germany, Great Britain, and the USA (McGourty, 1989).

With this in mind, we have constructed two additional scenarios in which the 1986 global CFC production listed in Table I is phased out by 2000, and by 1996, respectively.

*Scenario F.* In this scenario the production of CFCs is phased out in four steps by 2000, i.e.:

(i) the 1986 production stays constant until mid-1989;
(ii) a 20 per cent reduction of the 1986 level by mid-1990;
(iii) a 50 per cent reduction of the 1986 level by mid-1994;
(iv) a phase-out by 2000.

*Scenario G.* Same as scenario F but the global production of CFCs is phased-out as early as 1996, i.e.:

(i) the 1986 production stays constant until mid-1989;
(ii) a 20 per cent reduction of the 1986 level by mid-1990;
(iii) a 50 per cent reduction of the 1986 level by mid-1993;
(iv) a phase-out by 1996.

These six scenarios (i.e. not including A) are likely to span the total range of future CFC production developments.

## EMISSION SCENARIOS

The emission patterns of CFCs depend upon their uses. In some cases emission is prompt, in others it is delayed and occurs during usage and disposal. The emission of CFCs for the various scenarios have been determined from CFC production as follows.

Products of CFC-11 and CFC-12 can be divided into four categories:

(i) *Prompt emitters* (aerosol, open cell foam, solvents and cleaning agents) release CFCs shortly after manufacture. It has been assumed that the released emissions from such applications take place 6 months after production. According to Gamlen *et al.* (1986) the uncertainty in this 6-month figure is about 1 month.

(ii) *Hermetically sealed refrigeration units* (home refrigerators and freezers) have estimated mean lifetimes of 12 years (with a standard deviation of 4 years) during which small amounts of CFCs are released when some units fail (McCarthy *et al.*, 1977). An initial processing and testing loss of 3 per cent and a system rework loss of 5 per cent are also assumed (Rand, 1980).

(iii) *Non-hermetically sealed units* (building chillers and mobile air conditioners) lose CFCs through leakage and servicing throughout their lifetimes, estimated to be 7 years (Hammitt *et al.*, 1987). An estimated manufacturing loss of approximately 2·5 per cent is also taken into account (McCarthy *et al.*, 1977).

(iv) *The closed cell foam* category can be subdivided into rigid polyurethane and isocyanurate foams and non-urethane foams, and extruded polyolefines (Rand, 1980). The release of CFC-11 from closed cell foam (mainly rigid polyurethane foam) is the least well defined. In the present paper we have used the McCarthy *et al.* (1977) estimates of a production loss of 10 per cent, followed by a uniform loss of 4·5 per cent per year for 20 years. CFC-12 is primarily used in polyolefin foam, which does not retain blowing agents for long time periods. In this paper 50 per cent is considered to be lost in the year of manufacture, and the other half in the following year (Gamlen *et al.*, 1986).

CFC-113 is widely used as a solvent, among others in the electronics industries. Most of it is emitted promptly, but an estimated 15 per cent of the production is lost in waste disposal, dumps, and incinerators or used as an intermediary in manufacturing other chemicals (Hammitt *et al.*, 1987). Thus, for calculation purposes, we assume that world emission of CFC-113 is 85 per cent of world production.

CFC-114 and CFC-115 are mainly used in foams and refrigeration units. For these chemicals there is not much information available on which to base estimates of current and future emissions. We therefore assume that emission and production are the same.

The resulting emissions and corresponding production levels of CFCs for the seven scenarios as discussed in the previous section are given in Table II. All global emissions are presented in kilotonnes per year. The shares of end-use categories of CFC-11 and CFC-12 are taken from Chemical Manufacturers Association (1987) for the year 1985 and assumed to remain constant thereafter. In Table II it is interesting to note that the release of CFC-11 and CFC-12 to the atmosphere does not occur at the time of production or even soon after, because for some uses, including refrigeration, air conditioning devices, and closed cell foam, these chemicals are retained for long periods in a 'bank' (i.e. a large reservoir of potential ozone depleting chemicals) and this contributes significantly to any future release.

Table II. Calculated production (emission) values (kt year$^{-1}$) of CFCs to be controlled by the Montreal Protocol for a variety of scenarios

| | | Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| Chemical | Year | A | B | C | D | E | F |
| CFC-11 | 1986 | 401·2 (322·4) | 401·2 (322.4) | 401·2 (322·4) | 401·2 (322·4) | 401·2 (322·4) | 401·2 (322·4) |
| | 2000 | 709·3 (720.7) | 755·2 (709·0) | 428·4 (407·3) | 573·3 (538·6) | 242·3 (214·9) | 0·0 (145·2) |
| | 2030 | 3433·1 (3146·3) | 1459·0 (1380·8) | 1277·3 (1189·9) | 406·4 (396·8) | 212·2 (203·2) | 0·0 (0·0) |
| | 2050 | 8109·0 (7347·9) | 3332·1 (3097·7) | 3150·3 (2096·4) | 406·4 (396·8) | 212·2 (203·2) | 0·0 (0·0) |
| CFC-12 | 1986 | 497·8 (412·2) | 497·8 (412·2) | 497·8 (412·2) | 497·8 (412·2) | 497·8 (412·2) | 497·8 (412·2) |
| | 2000 | 862·0 (778·4) | 896·6 (984·7) | 485·4 (596·3) | 711·5 (662·7) | 293·8 (400·7) | 0·0 (171·0) |
| | 2030 | 2795·9 (2195·1) | 1327·2 (1238·2) | 1098·9 (965·1) | 503·9 (482·7) | 259·9 (210·8) | 0·0 (0·0) |
| | 2050 | 6126·1 (5000·7) | 2426·2 (2074·4) | 2197·9 (1954·0) | 503·9 (482·7) | 259·9 (210·8) | 0·0 (0·0) |
| CFC-113 | 1986 | 157·8 (133·2) | 157·8 (133·2) | 157·8 (133·2) | 157·8 (133·2) | 157·8 (133·2) | 157·8 (133·2) |
| | 2000 | 273·3 (230·6) | 288·0 (243·1) | 153·9 (129·9) | 299·4 (193·6) | 93·1 (78·6) | 0·0 (0·0) |
| | 2030 | 886·3 (748·0) | 422·6 (356·7) | 348·3 (294·0) | 161·6 (136·4) | 82·4 (69·5) | 0·0 (0·0) |
| | 2050 | 1941·9 (1693·0) | 770·9 (650·7) | 696·7 (588·0) | 161·6 (136·4) | 82·4 (69·5) | 0·0 (0·0) |
| CFC-114 | 1986 | 14·9 (14·9) | 14·9 (14·9) | 14·9 (14·9) | 14·9 (14·9) | 14·9 (14·9) | 14·9 (14·9) |
| | 2000 | 25·8 (25·8) | 27·9 (27·9) | 14·5 (14·5) | 22·4 (22·4) | 8·8 (8·8) | 0·0 (0·0) |
| | 2030 | 87·0 (87·0) | 40·3 (40·3) | 32·9 (32·9) | 15·6 (15·6) | 7·8 (7·8) | 0·0 (0·0) |
| | 2050 | 183·4 (183·4) | 73·2 (73·2) | 65·8 (65·8) | 15·6 (15·6) | 7·8 (7·8) | (0·0 (0·0) |
| CFC-115 | 1986 | 4·9 (4·9) | 4·9 (4·9) | 4·9 (4·9) | 4·9 (4·9) | 4·9 (4·9) | 4·9 (4·9) |
| | 2000 | 8·5 (8·5) | 9·2 (9·2) | 4·8 (4·8) | 7·4 (7·4) | 4·9 (4·9) | 0·0 (0·0) |
| | 2030 | 28·6 (28·6) | 13·3 (13·3) | 10·8 (10·8) | 5·2 (5·2) | 2·6 (2·6) | 0·0 (0·0) |
| | 2050 | 60·3 (60·3) | 24·1 (24·1) | 21·6 (21·6) | 5·2 (5·2) | 2·6 (2·6) | 0·0 (0·0) |

## CONCENTRATION SCENARIOS

At present the most abundant of the controlled CFCs in the atmosphere are CFC-11, CFC-12, and CFC-113 because of their large production rates and their long lifetimes. The respective global mean surface concentrations in 1986 were *ca.* 0·23 ppb, 0·39 ppb, and 0·05 ppb, respectively (Table I). Although the present concentrations of CFC-114 and CFC-115 are, at 0·02 ppb and 0·006 ppb, still small, in future they are expected to grow rapidly owing to their long lifetimes.

To convert the estimates of future CFC emission into concentration over the period 1986–2050, we have used the following mass balance equation:

$$C(t)=C(t-1)+[E(t)-\mathrm{MASS}(t-1)/\tau]\times CF$$

In this equation, the annual concentration ($C$) in year $t$ is a function of the previous year's concentration ($C(t-1)$), the emission in year $t(E(t))$, the atmospheric mass of a particular CFC in year $t-1$ ($\mathrm{MASS}(t-1)$), the atmospheric lifetime ($\tau$) and $CF$, which is a factor to convert emission from tons to ppbv (Table I).

Table III. Comparison of estimated CFC concentration ranges (ppbv) controlled by the Montreal Protocol for 2030

| Source | CFC-11 | CFC-12 | CFC-113 | CFC-114 | CFC-115 |
|---|---|---|---|---|---|
| This study[a] | 0·51–2·12 | 0·91–3·00 | 0·13–0·47 | 0·03–0·07 | 0·01–0·03 |
| Ramanathan *et al.* (1985) | 0·50–2·12 | 0·90–3·50 | 0·08–0·30 | 0·06–0·25 | 0·02–0·09 |
| Dickinson and Cicerone (1986) | 0·55–1·60 | 1·45–2·50 | – | – | – |
| Hammitt *et al.* (1987) | 0·62–1·33 | 1·19–2·51 | 0·20–0·65 | – | – |
| Wigley (1988)[b] | 0·53–1·05 | 0·90–1·79 | – | – | – |

[a] The ranges correspond to scenario E(low) and A(high).

[b] The low value corresponds to his scenario 1, which is similar to our scenario E. The low and high values were taken from the captions of his figures 2 and 3.

Table IV. Estimated concentrations (ppbv) of CFCs to be controlled by the Montreal Protocol for a variety of scenarios

| | | Scenario | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Chemical | Year | A | B | C | D | E | F | G |
| CFC-11 | 1986 | 0·234 | 0·234 | 0·234 | 0·234 | 0·234 | 0·234 | 0·234 |
| | 2000 | 0·475 | 0·483 | 0·418 | 0·456 | 0·388 | 0·343 | 0·315 |
| | 2030 | 2·124 | 1·311 | 1·044 | 0·781 | 0·509 | 0·253 | 0·226 |
| | 2050 | 5·663 | 2·583 | 2·241 | 0·910 | 0·548 | 0·193 | 0·173 |
| CFC-12 | 1986 | 0·395 | 0·395 | 0·395 | 0·395 | 0·395 | 0·395 | 0·395 |
| | 2000 | 0·732 | 0·805 | 0·705 | 0·711 | 0·679 | 0·596 | 0·542 |
| | 2030 | 3·001 | 2·806 | 1·603 | 1·414 | 0·912 | 0·460 | 0·413 |
| | 2050 | 6·729 | 3·541 | 2·909 | 1·687 | 1·018 | 0·384 | 0·344 |
| CFC-113 | 1986 | 0·054 | 0·054 | 0·054 | 0·054 | 0·054 | 0·054 | 0·054 |
| | 2000 | 0·123 | 0·130 | 0·106 | 0·122 | 0·097 | 0·082 | 0·073 |
| | 2030 | 0·467 | 0·316 | 0·241 | 0·207 | 0·128 | 0·059 | 0·052 |
| | 2050 | 1·051 | 0·540 | 0·443 | 0·245 | 0·142 | 0·047 | 0·042 |
| CFC-114 | 1986 | 0·020 | 0·020 | 0·020 | 0·020 | 0·020 | 0·020 | 0·020 |
| | 2000 | 0·028 | 0·029 | 0·026 | 0·028 | 0·025 | 0·023 | 0·022 |
| | 2030 | 0·070 | 0·053 | 0·042 | 0·039 | 0·028 | 0·020 | 0·019 |
| | 2050 | 0·145 | 0·082 | 0·068 | 0·045 | 0·030 | 0·018 | 0·017 |
| CFC-115 | 1986 | 0·006 | 0·006 | 0·006 | 0·006 | 0·006 | 0·006 | 0·006 |
| | 2000 | 0·009 | 0·010 | 0·009 | 0·009 | 0·008 | 0·008 | 0·007 |
| | 2030 | 0·026 | 0·020 | 0·016 | 0·015 | 0·010 | 0·007 | 0·007 |
| | 2050 | 0·056 | 0·032 | 0·026 | 0·018 | 0·012 | 0·007 | 0·006 |

Our calculation of atmospheric concentration of CFCs assumed a constant lifetime (Table I). In reality, the lifetimes depend on the stratospheric losses of CFCs and should be calculated accurately with photochemical models. The modelling of such processes is beyond the scope of this study. Table III shows the estimated CFC concentration calculated by various authors for the year 2030. The lower estimates are subject to a considerable range of uncertainty owing to the fact that most of the earlier studies have neglected possible emission reductions from future regulation of CFC-production. Only Wigley (1988) has estimated the CFC-11 and 12 concentrations for the scenarios possible under the present provisions of the Protocol. His scenario 1 is similar to our scenario E and our results are in good agreement with his findings. Our high estimate, which corresponds to the pre-Protocol scenario A, falls within the range of the other findings.

The calculated global mean of CFC concentrations from 1986 to 2050 for the various scenarios (scenarios A–G) are shown in Table IV. In the scenarios that are consistent with the Montreal Protocol provisions (scenarios B–E) and in the pre-Protocol scenario A, CFC concentrations continue to rise beyond 2050. It is only in scenarios F and G, which go beyond the Montreal Protocol in that they assume a complete phase-out of CFC production, that the concentration trends are reversed and slowly reducing as early as 2000 (scenario F) and even as early as 1997 (scenario G). This means that stabilization to current concentrations or below requires much greater than a 50 per cent cut-back.

## FUTURE IMPLICATIONS FOR CLIMATE CHANGE

The warming potential of CFCs was recognized only about a decade ago, when it was found that the addition to the atmosphere of one molecule of CFCs can have the same greenhouse effect as the addition of about $10^4$ molecules of $CO_2$ (Ramanathan, 1975). The radiation effect of CFCs over the past 30 years was about one-third that of $CO_2$ added over the same period (Dickinson and Cicerone, 1986). In the present study, a global radiative mean CFC concentration ($\Delta C_w$ in ppbv) is used to calculate the combined radiative forcing ($\Delta Q$ in $W\,m^{-2}$) as defined by (see Appendix)

$$\Delta Q = \Delta C_w$$

with

$$\Delta C_w = 0{\cdot}308\ \{0{\cdot}87\ C[\text{CFC-11}]_t + C[\text{CFC-12}]_t + 1{\cdot}42\ C[\text{CFC-113}]_t + 1{\cdot}64\ C[\text{CFC-114}]_t + 1{\cdot}2\ C[\text{CFC-115}]_t\}$$

where $C[X]_t$ is the concentration of component $X$ at time $t$. We have used this formulation because it is straight forward and the steady-state warming can be calculated directly.

Finally, the change in $\Delta Q$ can be approximately related to equilibrium surface temperature change $\Delta T_s$ by the following relation (Dickinson, 1982; Ramanathan *et al.*, 1985):

$$\Delta T_s = \lambda \Delta Q$$

where $\lambda$ is the climate sensitivity parameter. As shown by Ramanathan *et al.* (1985), the $\lambda$ values from a variety of one-dimensional radiative–convective model calculations range from 0·47 to 0·53 $K\ W^{-1}\,m^{-2}$. In our calculations we have used their latest estimate of 0·52. In this case a doubling of $CO_2$ would yield an equilibrium surface warming of about 2·3°C, which falls within the climate sensitivity of 1·5–4·5°C obtained by general circulation models. It should be mentioned here that the actual warming will be less than the equilibrium warming due to ocean heat inertia.

There are a number of CFCs not considered by the Montreal Protocol, which may eventually make a noticeable contribution to global warming, particularly in view of their long lifetimes and large anticipated growth rates. We have therefore assessed in Table V the radiative forcing and surface warming of eight other CFCs using the information given by Ramanathan *et al.* (1985).

Table VI summarizes the calculated change in radiative forcing from 1986 to 2050 by gas and scenario. Among the CFCs, CFC-11 and CFC-12 have the largest warming effect in all scenarios. Over the period 1986–2050, the CFC-11 and CFC-12 radiative forcing ranges from 1·1 $W\,m^{-1}$ to 0·1 $W\,m^{-1}$ and from

Table V. Concentration ($\Delta C$), radiative forcing ($\Delta Q$), and temperature change ($\Delta T_s$) of other CFCs

| Compound | $Q$ for $C=1$ ppb ($\mathrm{W\,m^{-2}}$) | $\Delta C_{1986}$ (ppb) | Growth rate (per cent $\mathrm{year^{-1}}$) | $\Delta Q_{1986}$ ($\mathrm{W\,m^{-2}}$) | $\Delta T_{s_{1986}}$ (°C) | $\Delta C_{2050}$ (ppb) | $\Delta Q_{2050}$ ($\mathrm{W\,m^{-2}}$) | $\Delta T_{s_{2050}}$ (°C) |
|---|---|---|---|---|---|---|---|---|
| $CCl_4$ | 0·15 | 0·143 | 1·7 | 0·021 | 0·0110 | 0·420 | 0·063 | 0·033 |
| $CF_4$(F-14) | 0·12 | 0·081 | 2·5 | 0·010 | 0·0050 | 0·393 | 0·047 | 0·024 |
| $CHClF_2$ (F-22) | 0·10 | 0·084 | 5·6 | 0·008 | 0·0040 | 2·746 | 0·275 | 0·143 |
| $CH_3CCl_3$ | 0·04 | 0·185 | 4·8 | 0·007 | 0·0030 | 3·718 | 0·149 | 0·077 |
| $CClF_3$ (F-13) | 0·42 | 0·009 | 4·4 | 0·004 | 0·0020 | 0·142 | 0·059 | 0·031 |
| $CH_2Cl_2$ | 0·06 | 0·037 | 3·9 | 0·002 | 0·0010 | 0·428 | 0·026 | 0·014 |
| $CHCl_3$ | 0·12 | 0·011 | 2·2 | 0·001 | 0·0005 | 0·044 | 0·005 | 0·003 |
| $C_2F_6$ (F-116) | 0·25 | 0·005 | 3·3 | 0·001 | 0·0005 | 0·039 | 0·010 | 0·005 |
| Total | | | | 0·054 | 0·0270 | | 0·634 | 0·330 |

This table has been compiled from tables 1 and 6 of Ramanathan *et al.* (1985)

Table VI. Estimated changes in radiative forcing ($\mathrm{W\,m^{-2}}$) due to the CFCs controlled by the Montreal Protocol

| Year | CFC-11 | CFC-12 | CFC-113 | CFC-114 | CFC-115 | Total |
|---|---|---|---|---|---|---|
| 1986 | 0·063 | 0·122 | 0·024 | 0·010 | 0·002 | 0·221 |
| *Scenario A* | | | | | | |
| 2000 | 0·125 | 0·226 | 0·054 | 0·014 | 0·003 | 0·422 |
| 2030 | 0·551 | 0·777 | 0·204 | 0·035 | 0·010 | 1·577 |
| 2050 | 1·466 | 1·722 | 0·459 | 0·073 | 0·021 | 3·741 |
| *Scenario B* | | | | | | |
| 2000 | 0·129 | 0·262 | 0·057 | 0·015 | 0·004 | 0·467 |
| 2030 | 0·351 | 0·642 | 0·138 | 0·027 | 0·007 | 1·165 |
| 2050 | 0·692 | 1·091 | 0·236 | 0·041 | 0·012 | 2·072 |
| *Scenario C* | | | | | | |
| 2000 | 0·112 | 0·223 | 0·046 | 0·013 | 0·003 | 0·397 |
| 2030 | 0·280 | 0·494 | 0·105 | 0·021 | 0·006 | 0·906 |
| 2050 | 0·600 | 0·896 | 0·194 | 0·034 | 0·010 | 1·734 |
| *Scenario D* | | | | | | |
| 2000 | 0·122 | 0·250 | 0·053 | 0·014 | 0·003 | 0·442 |
| 2030 | 0·211 | 0·435 | 0·090 | 0·020 | 0·005 | 0·761 |
| 2050 | 0·244 | 0·520 | 0·107 | 0·023 | 0·007 | 0·901 |
| *Scenario E* | | | | | | |
| 2000 | 0·104 | 0·209 | 0·042 | 0·013 | 0·003 | 0·371 |
| 2030 | 0·136 | 0·279 | 0·056 | 0·021 | 0·004 | 0·496 |
| 2050 | 0·147 | 0·313 | 0·062 | 0·015 | 0·004 | 0·541 |
| *Scenario F* | | | | | | |
| 2000 | 0·092 | 0·184 | 0·036 | 0·012 | 0·003 | 0·327 |
| 2030 | 0·068 | 0·142 | 0·026 | 0·014 | 0·003 | 0·253 |
| 2050 | 0·052 | 0·118 | 0·020 | 0·009 | 0·002 | 0·201 |
| *Scenario G* | | | | | | |
| 2000 | 0·084 | 0·167 | 0·032 | 0·011 | 0·003 | 0·297 |
| 2030 | 0·061 | 0·127 | 0·023 | 0·009 | 0·002 | 0·222 |
| 2050 | 0·046 | 0·106 | 0·018 | 0·008 | 0·002 | 0·180 |

1·6 $\mathrm{W\,m^{-1}}$ to 0·2 $\mathrm{W\,m^{-2}}$ (scenarios A–E). The contribution of CFC-113, CFC-114, and CFC-115 is negligible at present, but their effects will increase in future if the production of these compounds is not drastically reduced. Over the period 1986–2030, the combined radiative forcing due to the five CFCs (11, 12, 113, 114, 115) controlled by the Protocol and the eight other CFCs listed in Table V amounts to between

1·57 $\mathrm{W\,m^{-2}}$ and 0·49 $\mathrm{W\,m^{-2}}$ (scenarios A–E). The CFC forcing estimated by Wigley (1988) over the same period ranges between 0·87 $\mathrm{W\,m^{-2}}$ and 0·31 $\mathrm{W\,m^{-2}}$ (for his pre- and post-Protocol scenarios). Wigley (1988) has underestimated the radiative forcing because he assumed that the future production of all non-controlled CFCs would also change according to Protocol provisions.

Figure 1 shows the estimated equilibrium warming trends due to the CFCs controlled by the Montreal Protocol for scenarios A–G. Several interesting and rather surprising features emerge from the results shown in Figures 1 and 2. By 2050, as compared with the 1986 value of 0·12°C, the contribution of the controlled CFCs to global warming could increase sixteen fold without any control measures (scenario A). With Montreal Protocol provisions, by 2050, the rate of warming could decrease 44–85 per cent (scenarios B–E), but the warming would still be some two to nine times higher than that of 1986. Very importantly, it is only scenarios F and G, the complete phase-out of the CFCs, that bring about a significant reduction in global

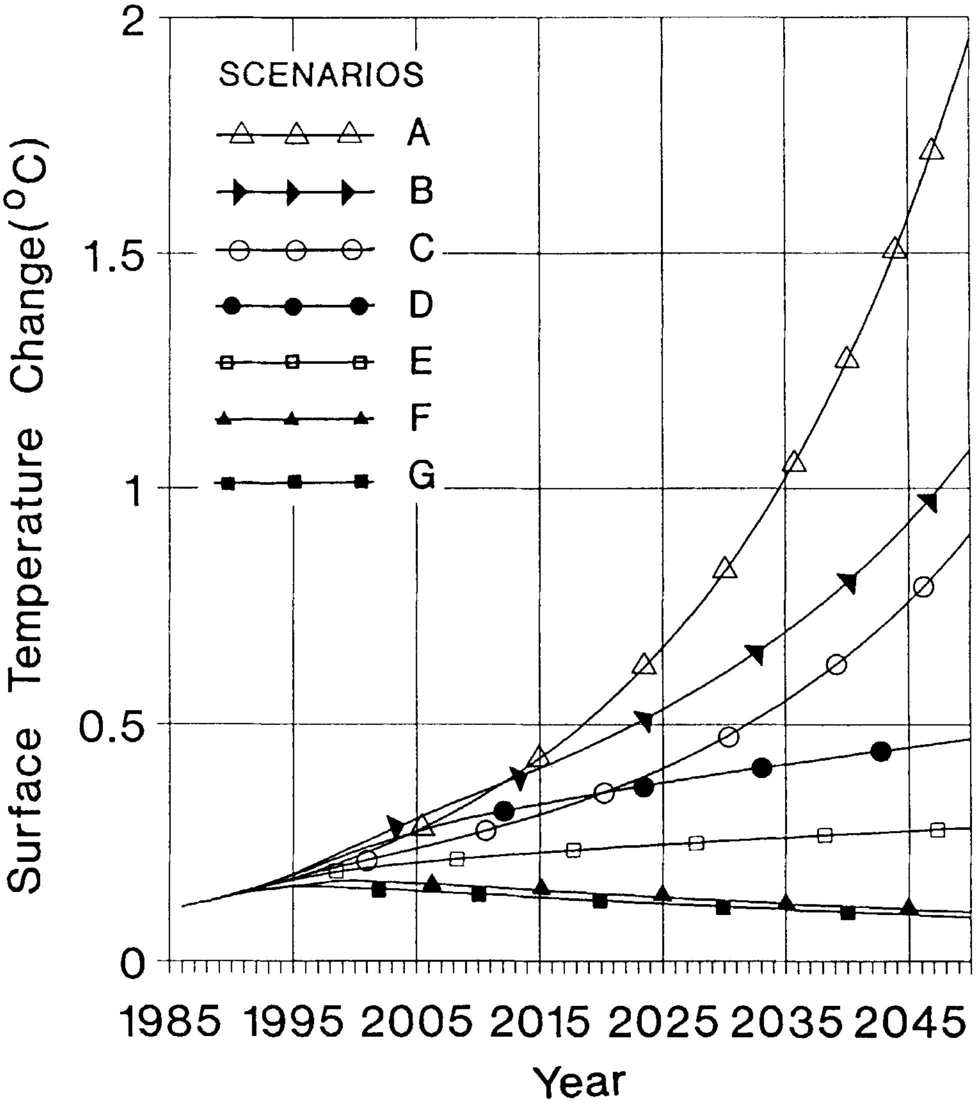

Figure 1. Calculated change in future global equilibrium warming (°C) due to the CFCs controlled by the Montreal Protocol for a variety of scenarios

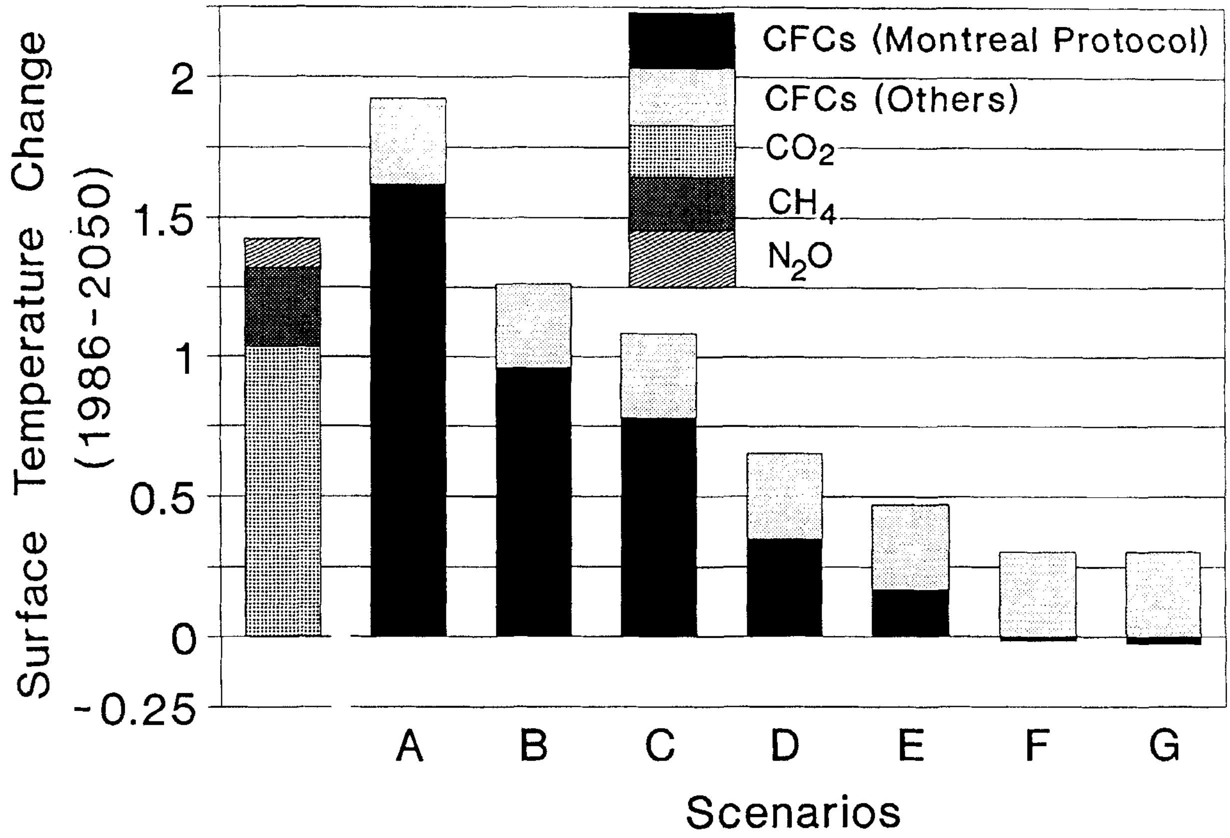

Figure 2. Estimated equilibrium surface temperature change (°C) due to trace gases ($CO_2$, $CH_4$, $N_2O$), and CFC scenarios in 2050 relative to 1986

warming. The highest value is reached at about 2000, reversing thereafter very slowly, although it is not until about 2040 (scenario F) and *ca.* 2030 (scenario G) that the 1986 level is again obtained.

In 1986, the combined surface warming contribution due to the other eight CFCs was 24 per cent of that for the five CFCs controlled by the Montreal Protocol. Without world-wide control, by 2050, it could increase by another 19 per cent in the case of the high scenario A, and by 31–165 per cent for scenarios B–E. Thus, it is necessary for these CFCs also to be brought under world wide control.

For assessing the future climatic effects of the other important trace gases, we have compared the warming potential of the CFCs with that of $CO_2$, $CH_4$, and $N_2O$ using the best model estimates of Dickinson and Cicerone (1986). Figure 2 shows the change in surface temperature over the period 1986–2050 by gas and scenario. The estimates are based on a model climate sensitivity of 2·3°C for a doubling of $CO_2$. The combined surface warming is 1·43°C, to which $CO_2$, $CH_4$, and $N_2O$ contribute about 71, 21, and 8 per cent, respectively. It is important to note that without control (scenario A) the surface warming due to all CFCs (i.e. controlled and uncontrolled) could even exceed that of the other trace gases by as much as 35 per cent. Figure 2 also indicates that under present Montreal Protocol provisions (scenarios B–E), the temperature increase due to CFCs could still become as large as 120–45 per cent of the $CO_2$ effect alone, and 88–33 per cent of $CO_2$, $CH_4$, and $N_2O$ combined.

## KEY FINDINGS

The main conclusions of this paper can be summarized as follows.

(i) Without control, the global equilibrium mean warming due to CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115 in 2050 could increase by sixteen times above the 1985 level (scenario A)

(ii) With present control provisions of the Montreal Protocol, the rate of warming would be reduced, but in 2050, they would still lead to temperatures that could be two to nine times higher than those in 1985 (scenarios B–E).

(iii) A phase-out of the CFCs controlled by the Montreal Protocol by 2000 or by 1996 would lead to an equilibrium surface temperature reduction in 2050 over the 1986 value of 9 and 18 per cent, respectively (scenarios F and G).

(iv) The contribution of eight additional CFCs—including carbon tetrachloride, methyl chloroform, and CFC-22 (Table V)—to the warming of the five CFCs controlled by the Montreal Protocol, was 24 per cent in 1986. By 2050, its share could increase by another 19 per cent (scenario A) and would therefore warrant serious control considerations.

(v) Without any control (scenario A), the global mean equilibrium surface temperature could increase by 3·35°C from 1986 to 2050 (for a climate sensitivity of 2·3°C). Of this the contribution of $CO_2$, $CH_4$, and $N_2O$ combined, the five CFCs of the Protocol, and the eight other CFCs would be 48, 43, and 9 per cent, respectively.

(v) A phase-out of the five CFCs of the Protocol by 2000 could significantly reduce the equilibrium greenhouse warming due to all considered trace gases by 49 per cent from 3·35°C to 1·71°C.

These findings of a substantial CFC contribution to global warming add strength to the urgency of a revision of the Montreal Protocol to protect both the ozone layer and the global climate.

## APPENDIX

For the CFCs we can assume a linear relationship between radiative forcing at the tropopause ($\Delta Q$) and surface concentration change ($\Delta C$). If $\Delta Q_i = a_i\, C_i$ for the $i$th CFC, then the combined forcing

$$\Delta Q = \sum_i \Delta Q_i = \sum_i a_i\, C_i$$

can be written as

$$\Delta Q = a \sum_i (a_i/a)\, C_i = a\, C_w$$

where $C_w$ (ppbv) is the weighted mean CFC concentration, and $a_i/a$ is the relative warming potential of the $i$th CFC. In the present study we have chosen $a$ to correspond to $a_i$ for CFC-12. According to Ramanathan *et al.* (1985), the radiative forcing of CFC-12 is $a = 0{\cdot}308\ \mathrm{W\,m^{-2}}$. Hence, after substituting the warming potentials of the CFCs given in Table I we have

$$\Delta Q = 0{\cdot}308\ C_w$$

with

$$C_w = 0{\cdot}87\ C[\text{CFC-11}] + C[\text{CFC-12}] + 1{\cdot}42\ C[\text{CFC-113}] + 1{\cdot}64\ C[\text{CFC-114}] + 1{\cdot}20\ C[\text{CFC-115}]$$

## REFERENCES

Anon. 1989. *Airborne Arctic Stratospheric Expedition, Preliminary Findings.*

Bach, W. 1984. *Our Threatened Climate: Ways of Averting the $CO_2$ Problem through Rational Energy Use*, Reidel, Dordrecht.

CMA 1987. *Production, Sales, and Calculated Release of CFC-11 and CFC-12 through* 1986, Chemical Manufacturers Association.

Dickinson, R. E. 1982. 'Modeling climatic changes due to carbon dioxide increases', in Clark, W. C. (ed.) *Carbon Dioxide Review*, Clarendon Press, New York, pp. 101–133.

Dickinson, R. E. and Cicerone, R. J. 1986. 'Future global warming from atmospheric trace gases', *Nature*, **319**, 109–115.

Enquete-Commission of German Parliament 1988. 'Schutz der Erdatmosphäre, Eine internationale Herausforderung (Protection of the Earth's atmosphere, an international challenge)', Zur Sache Nr. 5, Bonn (in German).

Environmental Protection Agency 1988a. *Regulatory Impact Analysis: Protection of Stratospheric Ozone*', EPA, Washington, DC.

Environmental Protection Agency 1988b. *Future Concentrations of Stratospheric Chlorine and Bromine*, EPA, Washington, DC.

Gamlen, P. H., Lane, B. C., Midgley, P. M. and Steed, J. M. 1986. 'The production and release to the atmosphere of $CCl_3F$ and $CCl_2F_2$ (chlorofluorocarbons CFC-11 and CFC-12)', *Atmos. Environ.*, **20**, 1077–1085.

Hammitt, J. K., Camm, F., Connell, P. S., Mooz, W. E., Wolf, K. A., Wuebbles, D. J. and Bamezai, A. 1987. 'Future emission scenarios for chemicals that may deplete stratospheric ozone', *Nature*, **330**, 711–716.

McCarthy, R. L., Bower, F. A. and Jesson, J. P. 1977. 'Production and release—world production and release of $CCl_3F_3$ and $CCl_2F_2$ (fluorocarbons 11 and 12) through 1975', *Atmos. Environ.*, **11,** 491–497.

McGourty, C. 1989. 'London ozone meeting wins some hearts', *Nature*, **338,** 101.

Molina, M. J. and Rowland, F. A. 1974. 'Stratospheric sink for chlorofluoromethanes: chlorine atom catalyzed destruction of ozone', *Nature*, **249,** 810–812.

Office of Technology Assessment 1988. 'An analysis of the Montreal Protocol on substances that deplete the ozone layer', Staff paper, Office of Technology Assessment, US Congress, Washington, DC.

Ozone Trends Panel Report 1988. Washington, DC.

Ramanathan, V. 1975. 'Greenhouse effect due to chlorofluorocarbons: climatic implications', *Science*, **190,** 50–52.

Ramanathan, V., Cicerone, R. J., Singh, H. B. and Kiehl, J. T. 1985. 'Trace gas trends and their potential role in climate change', *J. Geophys. Res.*, **90,** 5547–5566.

Rand 1980. *Economic Implications of Regulating Chlorofluorocarbon Emissions from Non-aerosol Applications*, Report issued by US Environmental Protection Agency, Washington, DC, EPA-560/12-80-001.

Rand 1986 *Projected Use, Emissions, and Banks of Potential Ozone-depleting Substances*, A Rand Note, Washington, DC, N-2282-EPA.

Reijnders, L. 1987. *Data on Chlorofluorocarbons*, Unpublished Report, Utrecht.

Rogers, J. D. and Stephens, R. D. 1988. 'Absolute infrared intensities for F-113 and F-114 and an assessment of their greenhouse warming potentials relative to other chlorofluorocarbons', *J. Geophys. Res.*, **93,** 2423–2428.

Stolarski, R. S. and Cicerone, R. J. 1974. 'Stratospheric chlorine: a possible sink for ozone', *Can. J. Chem.*, **52,** 1610–1615.

United Nations Environment Programme 1987. *Ad Hoc Scientific Meeting to Compare Model-generated Assessments of Ozone Layer Change for Various Strategies for CFC Control*, UNEP, Washington, DC.

Wang, W. C., Yung, Y. L., Lacis, A. A., Mo, T. and Hansen, J. E. 1976. 'Greenhouse effect due to man-made perturbation of trace gases', *Science*, **194,** 685–690.

Wigley, T. M. L. 1988. 'Future CFC concentrations under the Montreal Protocol and their greenhouse-effect implications', *Nature*, **335,** 333–335.