

CHAPTER 11

Halocarbon Scenarios for the Future Ozone Layer and Related Consequences

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CHAPTER 11

HALOCARBON SCENARIOS FOR THE FUTURE OZONE LAYER AND RELATED CONSEQUENCES

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SCIENTIFIC SUMMARY

- **Different future scenarios for the release of ozone-depleting substances (ODSs) into the atmosphere will have different consequences for atmospheric halogen loading and therefore for stratospheric ozone and surface ultraviolet (UV) radiation.** Such scenarios indicate the sensitivity of the ozone layer to possible additional future control measures and illustrate the effects of compliance with the Montreal Protocol. The scenarios are not designed to yield exact predictions of future ozone amounts, which are affected also by other factors including possible interactions with climate change associated with the increasing atmospheric concentrations of greenhouse gases and aerosols. These factors are not considered here, both because of uncertainties in predictability and to enable a more direct and simple comparison of the relative impacts of different future ODS production/emission scenarios.
- **Large reductions in the production and atmospheric release of ODSs have been achieved by international regulations (Montreal Protocol and its Amendments and Adjustments).** Without such controls, and assuming a (perhaps conservative) 3% annual growth rate in production, ODSs would have led to an equivalent effective stratospheric chlorine (EESC) loading of about 17 parts per billion (ppb) in 2050. The control measures of the original Montreal Protocol (1987) reduce this to about 9 ppb; the London Amendments (1990) to about 4.6 ppb; and the Copenhagen Amendments (1992) to about 2.2 ppb (but with effective chlorine loading increasing again in the second half of the 21st century). The Vienna Adjustments (1995) and the Montreal Amendments (1997) further reduce this to about 2.0 ppb (approximately the 1980 level) around the year 2050.
- **If there were to be an immediate stop to all emissions of human-made ODSs, including those currently in use, the future stratospheric halogen loading would not return to the 1980 level until about 2033.** On the other hand, with maximum production allowed by the current Protocol (Montreal Protocol and its Amendments and Adjustments as of 1997), the future stratospheric halogen loading is expected to decrease after about 1997 and to drop below the 1980 level in 2052.
- **Additional scenarios may affect the future ozone layer, although by amounts generally smaller than those already expected to be achieved by current regulations.** Relative to the current regulations (Montreal Protocol and its Amendments and Adjustments as of 1997), the equivalent effective chlorine loading above the 1980 level, integrated from now until the 1980 level is re-attained, could be decreased by
 - 9% by eliminating global Halon-1211 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1211 in existing equipment;
 - 7% by eliminating global Halon-1301 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1301 in existing equipment;
 - 5% by eliminating the global production of hydrochlorofluorocarbons (HCFCs) in the year 2004;
 - 2.5% by eliminating the global production of chlorofluorocarbons (CFCs) and carbon tetrachloride in the year 2004;
 - 1.6% by reducing the cap on HCFC production in developed countries from 2.8% to 2.0% and advancing the phase-out from the year 2030 to 2015, as well as more rapid intermediate reductions;
 - about 1% by eliminating the global production of methyl bromide in 2004.

The policy actions would advance the date at which the level of effective chlorine returns to the 1980 level by 1-3 years. It should be noted that if the currently allowed essential uses for metered dose inhalers (CFC-11, CFC-12, CFC-114) are extended from the year 2000 to 2004, the effective chlorine loading above the 1980 level would increase by 0.3%.

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- **Illegal production of ozone-depleting substances may delay the recovery of the ozone layer.** For example, illegal production of, in total, 20-40 ktonnes per year of CFC-12 and CFC-113 for the next 10-20 years would increase the equivalent effective chlorine loading above the 1980 level, integrated from now until the year the 1980 level is re-attained, by 1%-4% and delay the return to pre-1980 levels by about a year. Significant additional contributions may come from illegal production of halons.
- **Different scenarios of future effective chlorine loading lead to correspondingly different scenarios of future ozone amounts.** The exact ozone response is difficult to predict because of possible interactions with other global atmospheric changes. However, for the purpose of comparing the different scenarios, a simple scaling relationship between equivalent effective stratospheric chlorine loading and ozone depletion can be used if it is assumed that the ozone reductions observed during 1979-1991 were caused exclusively by the simultaneous increase in stratospheric effective chlorine. Within this approximation, the future evolution of ozone reductions follows closely the increases of effective chlorine above 1980 levels, with lowest ozone in about 1997, contemporaneous with maximum effective chlorine loading, and return to baseline (1980) values in 2052 (maximum production scenario) and 2033 (zero emissions scenario). At 45°N, the maximum reduction in the annually averaged ozone is expected to be about 15 Dobson units (DU), or about 4.3% lower than the 1980 value. At 45°S, the maximum reduction in the annually averaged ozone is expected to be about 20 DU, or about 6.2% lower than the 1980 value.
- **Decreases in the ozone column cause increases in surface UV radiation, if other factors (e.g., clouds, aerosols) remain unchanged.** For erythemally effective UV radiation (UV_{ery} , the integral of the product of the spectral irradiance and the spectral erythemal sensitivity), the temporal evolution of the scenario follows closely the increases of effective chlorine above 1980 levels, with highest UV irradiances in about 1997, contemporaneous with maximum effective chlorine loading, returning to baseline (1980) values in 2052 (maximum production scenario) and 2033 (zero emissions scenario). At 45°N, the maximum enhancement in the annually averaged UV_{ery} is expected to be about 4.7%, while at 45°S it is estimated to be about 8.1%.
- **Many other biological effects of UV exposure are recognized in addition to erythema and skin cancer induction.** These have a broad range of sensitivity to ozone changes, primarily because of different sensitivities of the biological effects to various wavelengths of radiation. In the few cases for which the biological spectral sensitivity functions (action spectra) are known, scaling factors are derived that allow estimation of the effective biological radiation for each of these effects, relative to the changes in erythemal radiation expected from future changes in effective stratospheric chlorine loading. The potential impacts of higher UV irradiances at the Earth's surface are discussed in detail by the UNEP Panel on the Environmental Effects of Ozone Depletion (UNEP, 1998b).
- **The compilation of Ozone Depletion Potentials (ODPs) has been updated and expanded.** The ODPs of halogen-containing molecules have been updated, relative to the previous Assessment, based on new estimates of atmospheric lifetimes.

11.1 INTRODUCTION

Halocarbon compounds produced by human activities are believed to have been the primary agents of the stratospheric ozone reductions observed in the past two decades, as discussed in the previous chapters. International agreements (the Montreal Protocol and its Amendments and Adjustments) have achieved large reductions in the production and atmospheric release of these compounds, and a slowing or turnover of the growth rates has already been observed in the tropospheric concentrations of some specific ozone-destroying substances (see Chapters 1 and 2). Even so, the recovery of the ozone layer is expected to take a number of decades, primarily because of the already high atmospheric burden and long lifetimes of some of these ozone-depleting substances (ODSs). Any additional future emission of ODSs will further delay this recovery.

The purpose of this chapter is to compare a number of possible future ODS production/emission scenarios and to estimate, according to current scientific understanding, their relative impacts on the rate and timing of the recovery of the ozone layer. Of particular interest are the effects of possible additional regulatory measures that define the range of human control available within the context of the atmospheric halogen loading already present.

It must be emphasized that the main question in this chapter is not the exact prediction of future ozone amounts, but rather the sensitivity of the ozone layer to different ODS emissions scenarios, especially those within human control that could result from more stringent or less stringent regulatory measures. The actual future state of the ozone layer is uncertain, not solely from imperfect scientific understanding of the relevant atmospheric processes, but in large part from the present inability to predict natural events such as major volcanic eruptions (which enhance ozone depletion by chlorine; see Chapter 12), factors related to social, political, and economic developments into the next century, and interactions between stratospheric ozone concentrations and other possible global-scale atmospheric changes (e.g., the build-up of greenhouse gases; see again Chapter 12).

The sequence of events considered in this chapter is illustrated schematically in Figure 11-1. Numerous industrially produced halocarbons have been identified as potentially ozone destroying. Following their production, the ODSs may be converted to other

compounds (with no emission to the atmosphere or effect on the ozone layer) or put into use where they can be effectively stored for considerable time before release to the atmosphere (e.g., halons in fire extinguishers). The delay times for release of these so-called banks of ODSs depend on their specific applications; in some cases, recovery and destruction of the banks is possible. Eventual emissions lead to the build-up of substantial reservoirs in the lower atmosphere (troposphere), where for many ODSs the destruction rates are slow due to their chemical inertness. However some other ODSs are destroyed mainly in the troposphere (e.g., hydrochlorofluorocarbons (HCFCs), methyl bromide), and for a few others, tropospheric destruction is also significant (e.g., Halon-1211). The surviving ODSs are gradually transported to the stratosphere. At sufficiently high altitudes in the stratosphere, enough short-wavelength ultraviolet (UV) radiation is available to photodissociate the ODSs and thus release ozone-destroying halogen

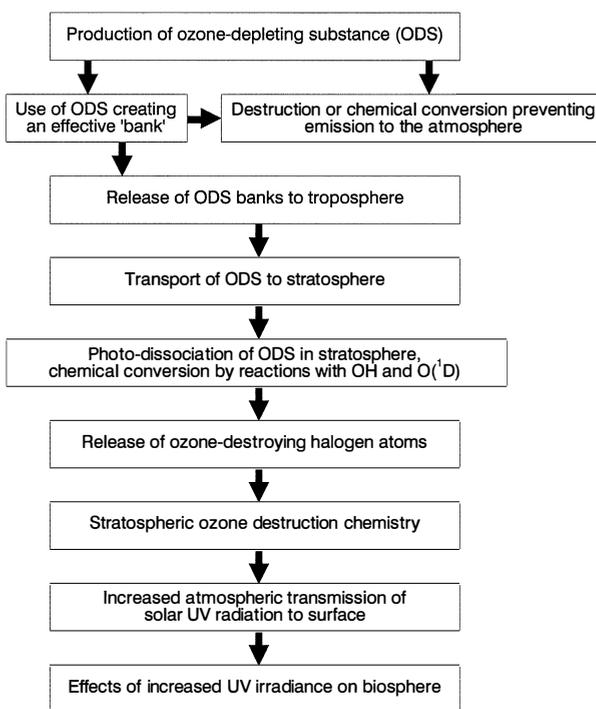


Figure 11-1. Chain of events connecting production of ozone-depleting substances (ODSs) to ultimate environmental effects of increased UV irradiance at the Earth's surface.

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atoms. Reactions of ODSs with hydroxyl radicals (OH) and excited-state oxygen atoms ($O(^1D)$) also result in the release of ozone-destroying halogen atoms in the stratosphere. Before eventual removal from the stratosphere, these halogens can lead to substantial reductions of the ozone layer and therefore to an increase in the transmission of solar UV radiation to the Earth's surface (see Chapter 9), especially in the biologically important ultraviolet-B (UV-B) wavelength band (280-315 nm). Such increases in surface UV radiation can lead to increased stresses on the biosphere. A number of detrimental effects of UV exposure have been identified, most prominently the induction of skin cancer, ocular damage, immune system suppression, and other potential human and animal health effects; damage to terrestrial and aquatic plants; and probably complex and subtle effects on ecosystem vitality and composition. The environmental consequences of increased UV radiation are discussed in detail in the report of the UNEP Panel on the Environmental Effects of Ozone Depletion (UNEP, 1998b).

In this chapter, insofar as the purpose is primarily to evaluate the relative effects of different ODS production/emission scenarios, this sequence of events is represented by applying a series of scaling relationships: the relative ozone-destroying effectiveness of the many different ODS compounds is parameterized here by their respective Ozone Depletion Potentials (ODPs; see WMO, 1995); their cumulative contribution to the stratospheric halogen content is represented by the equivalent effective stratospheric chlorine (EESC, which includes contributions from both chlorine and bromine species; see Section 11.4.1 for its definition); the relation between EESC and stratospheric ozone is taken from the observed ozone reductions and contemporaneous EESC increases in recent years (here, 1980 to 1990); and the changes in biologically active surface UV irradiance, resulting from stratospheric ozone changes, are estimated using radiative transfer calculations assuming that all other factors affecting surface UV radiation (e.g., clouds, aerosols, local pollutants) are held constant. It should be recognized that none of these factors are expected to remain strictly constant, although at present even the sign of possible future changes is unknown. The ultimate impacts of surface UV radiation changes on the biosphere are not discussed in detail here (but see UNEP, 1998b).

11.2 CURRENT CONTROL MEASURES AND ODPs

In 1985 the first international agreement to protect the ozone layer was signed: the Vienna Convention. This was followed in 1987 by the first international control measures, i.e., the Montreal Protocol on Substances that Deplete the Ozone Layer. Since then the Montreal Protocol has been amended and adjusted several times, with major changes occurring in 1990 (London Amendments), in 1992 (Copenhagen Amendments), in 1995 (Vienna Adjustments), and the latest in 1997 (Montreal Amendments). The Vienna Convention has been ratified by 166 countries, the Montreal Protocol by 165, the London Amendments by 121 countries, and the Copenhagen Amendments by 79 (as of June 1998).

The control measures in the Protocol apply to the production and consumption of classes of ozone-depleting substances (Annexes), i.e., chlorofluorocarbons (CFCs), halons, hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), and methyl bromide (CH_3Br). This means that it is permissible to exchange a certain amount of production from one substance to another in the same class, provided the total production is within the limits set by the Protocol. Within a class, substances are weighted by their Ozone Depletion Potentials (ODPs), defined as the integrated change in total ozone per unit mass emission of a specific compound, relative to the integrated change in total ozone per unit mass emission of CFC-11. The calculation of ODPs by several methods was described in detail in WMO (1995), and updated values are shown in Table 11-1. Significant revision is noted for methyl bromide, because of changes in estimates of its lifetime, and to a lesser extent for several HCFCs, because of revised estimates of the lifetime of methyl chloroform (see Chapter 2), from which estimates of lifetimes of HCFCs are scaled (Wuebbles *et al.*, 1998).

In the Montreal Protocol and its Amendments and Adjustments, a distinction is made, with respect to the control measures, between developing and developed countries. Any country that is a developing country and whose annual calculated consumption of CFCs and halons is less than 0.3 kg per year per capita is entitled to a delay of 10 years or more (see Table 11-2) to comply with the control measures that hold for developed countries. Countries for which this applies are termed in the Protocol as Article 5 paragraph 1 countries. Other

Table 11-1. Steady-State Ozone Depletion Potentials (ODPs).

	Trace Gas	Model-Derived ODP	Semiempirical ODP	ODP in Current Montreal Protocol ⁽¹⁾
Annex A-I	CFC-11	1.0	1.0	1.0
	CFC-12	0.82	0.9	1.0
	CFC-113	0.90	0.9	0.8
	CFC-114	0.85		1.0
	CFC-115	0.40		0.6
Annex A-II	CF ₃ Br (Halon-1301)	12	13	10.0
	CF ₂ ClBr (Halon-1211)	5.1	5	3.0
	C ₂ F ₄ Br ₂ (Halon-2402)			6.0
Annex B-II	CCl ₄	1.20		1.1
Annex B-III	CH ₃ CCl ₃	0.11 ⁽²⁾	0.12	0.1
Annex C-I	HCFC-22	0.034 ⁽²⁾	0.05	0.055
	HCFC-123	0.012 ⁽²⁾	0.02	0.02 [*]
	HCFC-124	0.026 ⁽²⁾		0.022 [*]
	HCFC-141b	0.086 ⁽²⁾	0.1	0.11 [*]
	HCFC-142b	0.043 ⁽²⁾	0.066	0.065 [*]
	HCFC-225ca	0.017 ⁽²⁾	0.025	0.025
	HCFC-225cb	0.017 ⁽²⁾	0.03	0.033
Annex E	CH ₃ Br	0.37 ⁽²⁾ (0.2-0.5) ⁽³⁾	0.57	0.6
Others	CF ₃ I	<0.008 ⁽²⁾	<0.008	
	CH ₃ Cl	0.02		
	HFC-134a	<1.5×10 ⁻⁵	<5×10 ⁻⁴	
	HFC-23	<4×10 ⁻⁴		
	HFC-125	<3×10 ⁻⁵		

* Corresponding isomer.

(1) Defined for regulatory purposes (UNEP, 1996).

(2) Update from WMO (1994) based on Wuebbles *et al.* (1998).

(3) See discussion in Chapter 2.

countries are termed Non-Article 5 paragraph 1 countries and comprise most of the developed countries.

Table 11-2 shows the current (since Montreal, September 1997) control measures for the different classes of substances and for both developed and developing countries. Currently the production and consumption of CFCs, halons, carbon tetrachloride, and methyl chloroform are phased out in the developed countries. The consumption (production+imports-

exports) of HCFCs and the production of methyl bromide are frozen in developed countries and have to be phased out by 2030 and 2005, respectively. The currently phased-out substances are still allowed to be produced by developed countries for some essential uses, and for use by the developing countries to meet their basic domestic needs. Developing countries must phase out CFCs, halons, and carbon tetrachloride in 2010 and methyl chloroform in 2015; regulation of HCFCs begins

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in 2016 with complete phase-out by 2040; and the production of methyl bromide has to be frozen in 2002 and phased out in 2015.

11.3 FUTURE EMISSIONS SCENARIOS

A set of future production and emission scenarios was constructed for ozone-depleting substances. The current control measures (Table 11-2) are used as the basis for the scenarios. Scenario A1 (see Tables 11-3 and 11-4) is the Baseline scenario, following the current regulations of the Montreal Protocol. Scenarios A2 and A4 describe the extreme cases with zero emissions and zero production, respectively, of ozone-depleting substances (ODSs). Scenario A3 describes the maximum production of ODSs allowed with the current control measures. Most other scenarios describe additional control measures on top of the Baseline scenario (A1). The additional control measures considered are a faster phase-out of CFCs, HCFCs, and methyl bromide, and the destruction of halons in existing equipment (halon banks). Also considered are the effects of illegal production of ODSs and essential-use exemptions. The potential effect of the different Amendments and Adjustments to the Montreal Protocol are also estimated. Table 11-3 gives the details of the scenarios.

The scenarios defined in this chapter are not designed to describe in the best possible way the future behavior of the chlorine and bromine species and of the depletion of the ozone layer, but rather to calculate the sensitivity of the EESC (indicator for the ozone layer; see Section 11.4.1) to possible additional future control measures, and to examine the effects of incomplete compliance with the Montreal Protocol. These scenarios are long-term scenarios, not intended to describe variations on time scales of a few years. Furthermore, with these scenarios we consider only their impact on the future ozone layer, not their role in other environmental issues such as, e.g., global warming. Most of the ODSs are greenhouse gases, and substances used as alternatives (e.g., HCFCs and hydrofluorocarbons (HFCs)) have smaller Ozone Depletion Potentials but are potent greenhouse gases (IPCC, 1996). Consideration of the effects of ODS reductions on different environmental issues could impose different constraints on future ODS scenarios (Wuebbles and Calm, 1997), which, however, are not considered here.

11.3.1 Baseline Scenario

The basis of the production and emission data of the Baseline scenario (A1) used here is given in Table 11-4. The emission data of all other scenarios are calculated by applying the conditions given in Table 11-3 to the production or emissions data of the Baseline (= reference) scenario. The scenarios with different control measures additional to the Montreal Amendments (1997) are assumed to start in 1996. The initial conditions for the scenarios (emissions and amount of substances present in the equipment as of 1995) are chosen to yield agreement with the atmospheric concentrations recently measured by the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) (Elkins *et al.*, 1998; Montzka *et al.*, 1996) and the Atmospheric Lifetime Experiment/Global Atmospheric Gases Experiment/Advanced Global Atmospheric Gases Experiment (ALE/GAGE/AGAGE) networks (Prinn *et al.*, 1998; see Chapters 1 and 2 of this Assessment). In Table 11-5 the ODS emissions for the Baseline scenario A1 are shown, while in Figure 11-2 the emissions are plotted by classes of substances (Annexes) weighted by their ODPs. Emissions of CFCs, carbon tetrachloride, and methyl chloroform have been decreasing since approximately the end of the 1980s (AFEAS, 1997). Before the phase-out of CFCs in the developed countries in 1996, the rate at which the emissions decreased depended on the amount produced and consumed and on the type of application and corresponding release time of the CFCs. The production of CFCs in developing countries was much smaller and is expected to be much smaller than the quantities produced in the developed countries in the 1980s; therefore, the emission from 1996 onward will be determined more by the quantities in the banks than by new production.

The production of CFCs reported by the developing countries to UNEP (1997b) is 107 ktonnes per year (ODP-weighted), while the maximum allowed production of CFCs for developing countries is 149 ktonnes per year from 1996 to 2004 (UNEP, 1994b). The production of CFCs in developing countries in 1995 in the Baseline scenario is 124 ktonnes per year (or 120 ktonnes-ODP weighted), increasing gradually to the maximum allowed production of 149 ktonnes per year in 2002.

The emissions are, for computational ease, calculated as a fraction of the bank for all scenarios. This

Table 11-2. Current (Montreal Amendments, September 1997 (UNEP, 1997d)) reduction and phase-out schedules for ozone-depleting substance (ODS) production and consumption^{1,2} for developed countries (Non-Article 5) and developing countries (Article 5).

	Developed countries (Non-Article 5)	Developing countries (Article 5)
CFC-11, -12, -113, -114, -115 (Annex A-I)	Base level ³ = 1986 1989: Freeze (July 1) ⁴ 1994: -75% 1996: Phase-out	Base level = Average of 1995-1997 1999: Freeze (July 1) 2005: -50% 2007: -85% 2010: Phase-out
Halons (Annex A-II)	Base level = 1986 1992: Freeze 1994: Phase-out	Base level = Average of 1995-1997 2002: Freeze 2005: -50% 2010: Phase-out
Other CFCs (Annex B-I)	Base level = 1989 1993: -20% 1994: -75% 1996: Phase-out	Base level = Average of 1998-2000 2003: -20% 2007: -85% 2010: Phase-out
Carbon tetrachloride (Annex B-II)	Base level = 1989 1995: -85% 1996: Phase-out	Base level = Average of 1998-2000 2005: -85% 2010: Phase-out
Methyl chloroform (Annex B-III)	Base level = 1989 1993: Freeze 1994: -50% 1996: Phase-out	Base level = Average of 1998-2000 2003: Freeze 2005: -30% 2010: -70% 2015: Phase-out
HCFCs consumption (Annex C-I)	Base level = 1989 + 2.8% of 1989 CFC 1996: Freeze 2004: -35% 2010: -65% 2015: -90% 2020: -99.5% 2030: Phase-out	Base level = 2015 2016: Freeze 2040: Phase-out
HBFCs (Annex C-II)	1996: Phase-out	1996: Phase-out
Methyl bromide (Annex E)	Base level = 1991 1995: Freeze 1999: -25% 2001: -50% 2003: -70% 2005: Phase-out + exemptions	Base level = Average of 1995-1998 2002: Freeze 2005: -20% 2015: Phase-out + exemptions

¹ Exemptions to the production and consumption of ODS are allowed in developed countries for essential uses and to meet the basic domestic needs of developing countries. The latter may be maximally 10-15% of the base-level production (CFCs, carbon tetrachloride, methyl chloroform, halons, and methyl bromide).

² In the Montreal Protocol, consumption is defined as production plus imports minus exports.

³ The reductions are always relative to the base level.

⁴ The control measures take effect on January 1 of the year indicated, unless indicated otherwise.

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Table 11-3. Description of scenarios for ozone-depleting substances (ODSs)¹. The Baseline scenario A1 (see Table 11-2) is used as the reference scenario for all other scenarios. When nothing is indicated for a substance, the values for the Baseline scenario are used.

	Developed countries (Non-Article 5)	Developing countries (Article 5)
Maximum/Minimum scenarios:		
A1: Baseline (Montreal Amendments 1997) = Reference	Baseline scenario according to the latest Amendments (1997) of the Montreal Protocol; see Table 11-4.	
A2: Zero emission	Emissions of all ODSs set to zero from 1999 onward; i.e., banks destroyed and production stopped.	
A3: Maximum production	Maximum production allowed for all ODSs with current (Montreal, 1997) control measures, including approved essential uses but no illegal production, i.e., A1 scenario plus 15% additional production (of the base level of CFC-11, CFC-12, CFC-113, carbon tetrachloride, and methyl chloroform) in developed countries for use in developing countries (data from UNEP (1994b)).	
A4: Zero production	Production of all ODSs set to zero from 1999 onward.	
CFC and carbon tetrachloride scenario:		
B3: Phase-out of CFCs and CCl ₄ by 2004	Production of CFCs and CCl ₄ set to zero from 2004 onward.	
HCFC scenarios:		
C1: Reduce HCFC cap to 2%	Reducing the HCFC consumption ¹ cap from 2.8% to 2.0% beginning in 2000 and phase-out in 2030.	
C2: Cap at 2% and phase-out of HCFCs by developed countries in 2015	Reducing the HCFC consumption cap from 2.8% to 2.0% beginning in 2000 and advancing the phase-out to 2015, with interim cuts of 35% in 2004, 60% in 2007, 80% in 2010, and 95% in 2013.	
C3: Global phase-out of HCFCs by 2004	Production of HCFCs set to zero from 2004 onward.	
	Developed countries (Non-Article 5)	Developing countries (Article 5)
Methyl bromide scenario:		
D3: Phase out CH ₃ Br by 2004	Production of methyl bromide set to zero from 2004 onward.	
Essential use scenarios:		
E1: No essential uses	All assigned essential uses (CFC-11, CFC-12, CFC-113, CFC-114, CH ₃ CCl ₃ , and Halon-2402) set to zero from 1996 onward (see Table 11-4) (UNEP, 1997a).	
E2: Essential uses for metered dose inhalers up to 2004	Essential uses for metered dose inhalers (MDIs) extended for the years 2000-2004: 3 ktonnes of CFC-11, 6 ktonnes of CFC-12, and 1 ktonne of CFC-114.	
Illegal production scenarios:		
F1: Illegal CFC production: low estimate	Noncompliance with the Protocol: low estimate for illegal CFC production: total of 20 ktonnes per year from 1996 through 2005 (CFC-12 and CFC-113 in a 2:1 ratio).	

Table 11-3, continued

	Developed countries (Non-Article 5)	Developing countries (Article 5)
F2: Illegal CFC production: high estimate	Noncompliance with the Protocol: high estimate for illegal CFC production: total of 40 ktonnes per year from 1996 through 2015 (CFC-12 and CFC-113 in a 2:1 ratio).	
F3: Illegal halon production	Noncompliance with the Protocol: illegal production of Halon-1211: 2 ktonnes per year from 1996 through 2005.	
Halon destruction scenarios:		
G1: Destruction of halon banks in 2000	No emission of halons (including from existing equipment) after 1999.	
G2: Destruction of Halon-1211 bank in 2000	No emission of Halon-1211 (including from existing equipment) after 1999.	
G3: Destruction of Halon-1301 bank in 2000	No emission of Halon-1301 (including from existing equipment) after 1999.	
G4: Destruction of Halon-2402 bank in 2000	No emission of Halon-2402 (including from existing equipment) after 1999.	
Amendments to the Protocol:		
H1: No Protocol	No limitations on the production and consumption of ODSs: a 3% annual growth of CFCs, carbon tetrachloride, methyl chloroform, halons, HCFC-22, and anthropogenic methyl bromide from 1986 onward. A 3% annual growth was also used in WMO (1995).	
H2: Montreal Protocol (1987)	Freeze of CFCs in 1989, reduction of CFCs by 20% in 1994, 50% in 1999; freeze in halons in 1992. Other species as in scenario H1; additional HCFC-22 production to fully compensate the reduced CFC and carbon tetrachloride production.	Same growth as in No Protocol case.
H3: London Amendments (1990)	Phase-out of CFCs, carbon tetrachloride, and halons by 2000 and methyl chloroform by 2005 (plus interim reductions). Allowing an additional 15% production after phase-out for use in developing countries. Other species as in scenario H1; additional HCFC-22 production to fully compensate by mass the reduced CFC and carbon tetrachloride production.	Applying the London Amendments with a 10-year grace period. Additional HCFC-22 production to fully compensate by mass the reduced CFC and carbon tetrachloride production.
H4: Copenhagen Amendments (1992)	Phase-out of CFCs, carbon tetrachloride, and methyl chloroform by 1996, halons by 1994, and HCFCs by 2030. This equals scenario A1 except methyl bromide fixed at 1991 level and a 3.1% cap for HCFCs.	Applying the Copenhagen Amendments with a 10-year grace period. This equals scenario A1 except a 3% annual growth in methyl bromide and a 3% annual growth in HCFCs until phase-out in 2040.
H5: Vienna Adjustments (1995)	HCFC cap reduced to 2.8% and methyl bromide emissions reduced by 25% in 2001, 50% in 2003, and 100% in 2010. The rest as in the A1 scenario.	Freeze of HCFC consumption by 2016 and phase-out in 2040 and a freeze in methyl bromide emissions by 2002. This equals scenario A1 except methyl bromide emissions constant at 1991 level.

¹ HCFC regulations apply to consumption. In these scenarios consumption and production are considered equal.

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Table 11-4. Basis of the production and emission estimates¹ for the Baseline scenario (A1).

Class of substances	Production and emission description
CFCs	<ul style="list-style-type: none"> • Developed countries: production is zero. • Developing countries: production increasing from the 1995 value to the maximum allowed value (UNEP, 1994b) in 2002. Reduction scheme according to the Protocol. • Essential uses for developed countries for CFC-11, CFC-12, CFC-113, and CFC-114 as approved by UNEP (1997a). No essential uses after 1999. • Bank in 1995: 1219 ktonnes for CFC-11, 791 ktonnes for CFC-12, 23.5 ktonnes for CFC-113, 22.6 ktonnes for CFC-114, and 31.2 ktonnes for CFC-115. • Emissions² based on analysis of emission patterns during the period 1990-1995: 9% of the calculated bank of the previous year for CFC-11, 25% for CFC-12, 14% for CFC-114, and 30% for CFC-115. The emission of CFC-113 is 50% of the production of the previous year plus 50% of the production of the current year.
Halons	<ul style="list-style-type: none"> • Developed countries: production is zero. • Developing countries: adapted from allowances under the Protocol (UNEP, 1994b) and reported data (UNEP, 1997b,c) (see McCulloch, 1992; Fraser <i>et al.</i>, 1998). Reduction schedule according to the Protocol. • Essential uses for the developed countries for Halon-2402 as approved by UNEP (1997a). No essential uses after 1998. • Bank in 1995: 67.6 ktonnes for Halon-1211, 75.2 ktonnes for Halon-1301, and 5.3 ktonnes for Halon-2402. • Emissions: 11% of the calculated bank of the previous year for Halon-1211, 4% for Halon-1301, and 20% for Halon-2402 (SORG, 1996).
Carbon tetrachloride	<ul style="list-style-type: none"> • The emissions are linked to the production of CFC-11 and CFC-12 as well as other production processes. Based on historic production and emission data, the emission of carbon tetrachloride is assumed to be equal to 8% of the production of CFC-11 and CFC-12 (Simmonds <i>et al.</i>, 1998). Taking the different molecular masses into account, the emission of carbon tetrachloride is represented by 8% of $[(154/137.5) \times \text{production CFC-11} + (154/121) \times \text{production CFC-12}]$.
Methyl chloroform	<ul style="list-style-type: none"> • Developed countries: production is zero (Midgley <i>et al.</i>, 1998). • Developing countries: production based on Midgley and McCulloch (1995) and UNEP (1994b). Reduction schedule according to the Protocol. • Essential uses approved for 1996-2001. • The emission is in the same year as the production.
HCFCs	<ul style="list-style-type: none"> • Developed countries: production capped at the HCFC production in 1989 plus 2.8% of the CFC production in 1989 (=33011 ODP tonnes per year) with distribution among the products as in the revised IS92a scenario (IPCC, 1996). No additional production for developing countries. • Developing countries: production is the difference between IS92a (IPCC, 1996) and the production in the developed countries. These numbers were interpolated from 5-year interval data (IPCC, 1996) to 1-year intervals. From 2016 to 2039 the production is fixed at the 2015 level. • Bank in 1995: 768 ktonnes for HCFC-22, 148 ktonnes for HCFC-141b, 76.1 ktonnes for HCFC-142b, and zero for HCFC-123. • Emissions: 28% of the calculated bank of the previous year for HCFC-22, 30% for HCFC-141b, 38% for HCFC-142b, and 5% for HCFC-123.
Methyl bromide	<ul style="list-style-type: none"> • Developed countries: in 1996 structural emissions of 4 ktonnes per year and agricultural emissions of 17 ktonnes per year (SORG, 1996 and Chapter 2), decreasing to zero in 2005 according to the Protocol. • Emission in developing countries (agricultural) and critical use exemptions: 18 ktonnes per year for all years (1996-2100). • Other emissions (e.g., natural) of methyl bromide, derived from the total loss of methyl bromide using a lifetime of 0.7 years (Chapter 2), amount to 167 ktonnes per year.

1 The assumptions made in this scenario differ slightly from those made in the previous Assessment (WMO, 1995). See also Section 11.4.4.

2 The emissions are, for computational ease, calculated as a fixed percentage (release fraction) of the bank of the previous year. These release fractions are not necessarily the representation of the actual emission from a specific application.

Table 11-5. Emissions of ozone-depleting substances (ktonnes per year) in the Baseline scenario (A1).

Year	CFC-11		CFC-113		CFC-115		CH ₃ CCl ₃	HCFC-141b		HCFC-123		Halon-1301		CH ₃ Br	
	CFC-12	CFC-114	CCl ₄	HCFC-22	HCFC-142b	Halon-1211	Halon-2402								
1990	250	371	236	10.3	12.2	63	718	178	0	9	0	10.3	3.4	1.8	206
1991	210	352	184	6.3	12.6	49	635	193	0	13	0	10.4	3.9	1.8	206
1992	172	330	149	5.2	12.6	49	593	194	14	41	0	10.2	3.9	1.8	206
1993	138	279	99	4.6	12.6	44	380	190	14	26	0	9.6	3.4	1.8	206
1994	118	236	61	4.0	11.9	45	283	195	29	25	0	8.9	3.2	1.8	206
1995	105	173	48	3.1	10.9	40	234	183	46	29	0	7.8	3.1	1.8	206
1996	110	198	22	3.2	9.4	12	5	215	45	29	0	7.4	3.0	1.1	206
1997	103	169	22	2.9	6.6	12	5	242	62	35	2	7.8	2.9	0.9	206
1998	97	149	22	2.7	4.6	12	5	282	69	42	5	8.0	2.8	0.8	206
1999	91	133	23	2.5	3.2	12	5	318	69	46	9	8.1	2.8	0.7	201
2000	86	122	23	2.2	2.2	12	5	350	65	49	14	7.9	2.7	0.6	201
2001	81	113	24	1.9	1.6	12	5	392	64	54	20	7.6	2.6	0.4	196
2002	77	106	25	1.6	1.1	12	5	423	63	57	25	7.2	2.6	0.4	195
2003	73	102	25	1.4	0.8	12	5	445	63	59	30	6.7	2.5	0.3	190
2004	70	99	25	1.2	0.5	12	5	461	63	60	35	6.3	2.4	0.2	189
2005	67	96	19	1.0	0.4	6	3	432	57	54	38	5.9	2.3	0.2	181
2006	62	83	16	0.9	0.3	6	3	424	55	52	41	5.6	2.3	0.1	181
2007	58	74	11	0.8	0.2	3	3	418	53	50	43	5.0	2.2	0.1	181
2008	54	61	9	0.7	0.1	3	3	414	51	49	46	4.5	2.1	0.1	181
2009	50	51	7	0.6	0.1	3	3	412	50	48	48	4.1	2.1	0.1	181
2010	46	44	4	0.5	0.1	0	1	412	49	47	51	3.7	2.0	0.1	181
2011	42	33	2	0.4	0.0	0	1	368	43	40	51	3.3	1.9	0.0	181
2012	38	25	2	0.4	0.0	0	1	336	39	36	51	3.0	1.8	0.0	181
2013	35	19	0	0.3	0.0	0	1	313	36	33	52	2.6	1.8	0.0	181
2014	32	14	0	0.3	0.0	0	1	296	34	32	52	2.3	1.7	0.0	181
2015	29	10	0	0.2	0.0	0	0	283	33	31	53	2.1	1.6	0.0	167
2016	26	8	0	0.2	0.0	0	0	232	27	24	51	1.9	1.6	0.0	167
2017	24	6	0	0.2	0.0	0	0	196	23	20	50	1.7	1.5	0.0	167
2018	22	4	0	0.1	0.0	0	0	169	20	17	49	1.5	1.4	0.0	167
2019	20	3	0	0.1	0.0	0	0	150	18	16	48	1.3	1.4	0.0	167
2020	18	2	0	0.1	0.0	0	0	137	16	15	46	1.2	1.3	0.0	167
2025	11	1	0	0.1	0.0	0	0	77	10	9	40	0.7	1.1	0.0	167
2030	7	0	0	0.0	0.0	0	0	66	9	8	34	0.4	0.9	0.0	167
2035	4	0	0	0.0	0.0	0	0	63	8	8	30	0.2	0.7	0.0	167
2040	3	0	0	0.0	0.0	0	0	62	8	8	27	0.1	0.6	0.0	167
2060	0	0	0	0.0	0.0	0	0	0	0	0	10	0.0	0.3	0.0	167
2080	0	0	0	0.0	0.0	0	0	0	0	0	3	0.0	0.1	0.0	167
2100	0	0	0	0.0	0.0	0	0	0	0	0	1	0.0	0.1	0.0	167

Baseline scenario (A1): Emission of trace gases

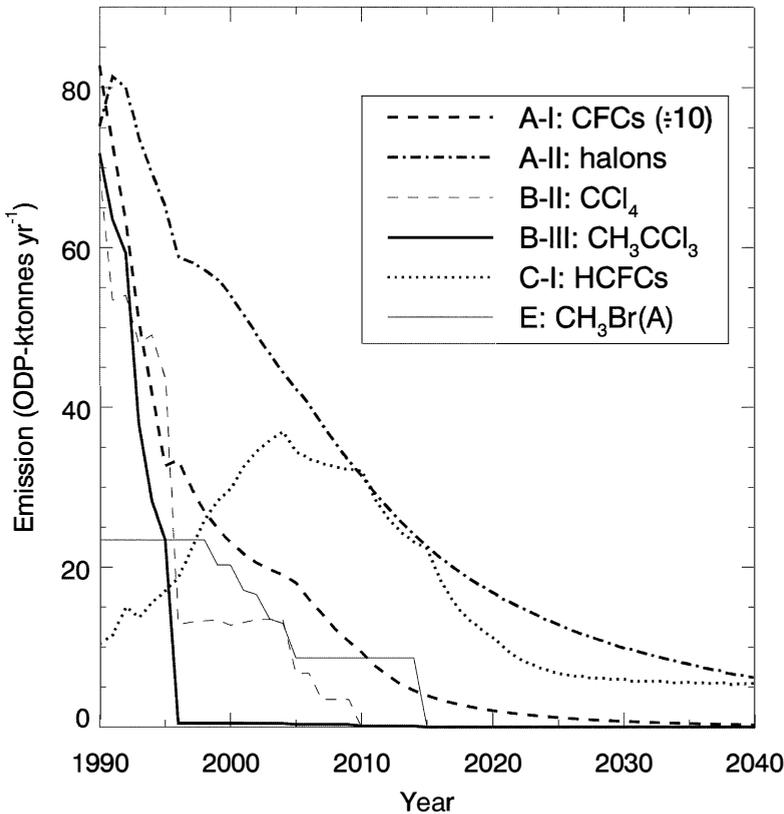


Figure 11-2. Emissions (ODP-weighted) of ozone-depleting substances of the Baseline scenario (A1). Note that CFC emissions were divided by a factor of 10 to be shown in this graph. For methyl bromide only the anthropogenic emissions are plotted. Substances are grouped by the Annexes (A-I, A-II,... E) defined in the Montreal Protocol.

fraction is based on an analysis of the quantities present in, and emitted from, the banks over the years 1990-1995. The banks and the emissions in this period are based on both emission inventories (e.g., AFEAS, 1997) and inverse modeling of the change in observed atmospheric concentrations. Each substance has its own release fraction, which is assumed to be constant from 1996 to 2100. Recycling and recovery of halocarbons are not considered explicitly in the scenarios.

11.3.2 Maximum and Minimum

After the phase-out date of CFCs, carbon tetrachloride, methyl chloroform, and halons in the developed countries, these substances are still allowed to be produced there for use in developing countries. The amount produced is maximally 15% of the base-level production. This additional production is accounted for in the Maximum production scenario (A3) for CFC-11, CFC-12, CFC-113, carbon tetrachloride, and methyl chloroform. The annual CFC production in developed countries for use in developing countries is almost equal

to the maximum allowable production in developing countries, i.e., 149 ktonnes per year in developing countries (through 2004, with lower values from 2005 to 2009) versus 152 ktonnes per year in developed countries (through 2009) (UNEP, 1994b). Additional allowed production of halons in developed countries after 1994 is ignored in scenario A3, because the production of halons in developed countries already ceased in 1994.

It does not seem very likely that developed countries will produce ODSs up to maximum allowed values. For example, production in developed countries for 1990-1993 was approximately 40% below the allowed limits (AFEAS, 1997), and developing countries may also be below their allowed limits.

While scenario A3 describes the maximum production allowed within the current regulations, scenario A2 is a Zero emission case: all emissions are set to zero from 1999 onward, which would require an immediate stop in production and consumption of all ODSs, and destruction or prevention of emission of all ODSs from existing or new applications. This scenario,

although unrealistic from a practical point of view, describes, together with the Maximum production scenario A3, the maximum range that currently exists for additional control measures to protect the ozone layer by reducing the emissions of ODSs.

11.3.3 Carbon Tetrachloride and Methyl Chloroform

Historically, the emission of carbon tetrachloride was well represented by approximately 8% of the production of CFC-11 and CFC-12 (Simmonds *et al.*, 1998). This 8% is considered to contain both emissions from production losses of CFCs and fugitive emissions from carbon tetrachloride usage itself. In the future scenarios of Table 11-3, carbon tetrachloride emissions are therefore described by the same relationship. Considering the rapid decline in the atmospheric concentration of carbon tetrachloride (Chapter 1), the 8% might overestimate the emissions in the future scenarios. On the other hand, the maximum allowed carbon tetrachloride production (UNEP, 1994b) could result in an emission amount that is a factor of 3 larger. After complete phase-out of CFCs in 2010, the emission of carbon tetrachloride is expected to be essentially zero.

Methyl chloroform production in the developed world has ceased already (Midgley *et al.*, 1998), while the maximally allowed production of methyl chloroform in developing countries is 4.6 ktonnes per year through 2004, with lower levels thereafter. In the A3 scenario, developed countries are allowed to produce 98.4 ktonnes per year to satisfy the demands in developing countries (UNEP, 1994b).

11.3.4 Halons

In the Baseline scenario (Table 11-4), the production of halons is zero from 1995 onward in developed countries (UNEP, 1997b). In developing countries, the production of halons in 1995 is 41 ktonnes per year (ODP-weighted) (UNEP, 1997b). From 1996 onward this amount is extrapolated and reduced according to data from UNEP (1997c) and the limits of the Montreal Protocol, and distributed in the Baseline scenario between Halon-1211 and Halon-1301 (Fraser *et al.*, 1998). The production is larger than the maximum allowed production envisaged by UNEP (1994b).

The calculated bank of Halon-1211 in 1995 is 67.6 ktonnes, which is close to the 65.3 ktonnes (for Western Europe, Australia, North America, and Japan) reported

by the Technology and Economic Assessment Panel (TEAP) of UNEP (1998a). The corresponding Halon-1211 emission we use for 1996 is 7.4 ktonnes per year (Table 11-5), which is more than twice the emission reported by TEAP of 3.4 ktonnes per year (UNEP, 1998a). The total emission of Halon-1211 in the 1980s and 1990s reported by TEAP is less than half of our emissions and cannot sustain the observed growth in atmospheric concentration (see Section 1.2.3 and Butler *et al.*, 1998).

The calculated bank of Halon-1301 in 1995 is 75.2 ktonnes compared with 38.0 ktonnes (for Western Europe, Australia, North America, and Japan) reported by TEAP (UNEP, 1998a). This difference is caused by the larger production of Halon-1301 for the whole period from 1975 to 1993 in the estimates we use (Fraser *et al.*, 1998) compared with those of TEAP. The bank estimated by TEAP does not include production from all developed countries and from the major developing countries, which according to UNEP (1997b) takes place. This might account for the different production and bank. The total emission we use for Halon-1301 from 1980 to 1995 of 58.2 ktonnes per year is only slightly larger than the 53.0 ktonnes per year reported by TEAP.

11.3.5 HCFCs

According to the Montreal Amendments of 1997 (Table 11-2), the consumption of HCFCs in developed countries is frozen in 1996. Reductions are mandatory from 2004 onward with a complete phase-out in 2030. Developing countries have to freeze their consumption of HCFCs in 2016 at the level of 2015, so there is no specified limit on their consumption (and production) until 2016. For HCFCs the Protocol deals with consumption; in this chapter the production of HCFCs is assumed to be equal to its consumption. A maximum allowable production level can therefore not be defined for HCFCs. The future HCFC production in developed and developing countries is estimated using the revised IS92a projections as reported in IPCC (1996). The production of HCFCs in developed countries is capped at the 1989 HCFC production plus 2.8% of the 1989 CFC production. Because the total production in developed countries was below the capped value in 1995, the maximum allowable production increases until 1999 and starts to decrease from 2004 onward following the reduction schedule of the Protocol. The HCFC production in developing countries is defined as the difference between the IS92a (IPCC, 1996) projections

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and the production in developed countries. From 2015 to 2039 the production is held constant, and it is zero from 2040 onward in accordance with the Protocol. Because there are no limitations on HCFC use in developing countries until 2016, the estimated future HCFC production is not the maximally allowed production. The corresponding HCFC production is larger in developed countries than in developing countries until 2015, when a larger reduction applies to developed countries.

11.3.6 Methyl Bromide

The emissions of all substances discussed above are entirely of anthropogenic origin. Methyl bromide has both natural and anthropogenic sources and has considerable uncertainties in the source strengths (Chapter 2). The anthropogenic emissions in 1995 are estimated at 21 ktonnes per year in developed countries and 18 ktonnes per year in developing countries and for critical-use exemptions for developed countries. The natural emissions from the oceans and biomass burning are estimated to be 76 ktonnes per year (Yvon-Lewis and Butler, 1997; SORG, 1996).

The total emission of methyl bromide required to balance the total known sinks is estimated as 206 ktonnes per year. The discrepancy between this sink-based estimate and the known emissions, 91 ktonnes per year, is currently thought to be of natural origin and was added to the natural source of 76 ktonnes per year in the scenarios discussed in this chapter. If instead the sink of methyl bromide has been overestimated, or if a significant fraction of the unknown source is of anthropogenic origin and controllable under the Montreal Protocol, then the effect of control measures on the effective chlorine loading could be larger than estimated here.

11.3.7 Uncertainties in Baseline Scenario

Although scenario A1 is constructed in an attempt to represent reasonable emissions under the Protocol, it is possible that the emissions could be larger.

First, the reduction and phase-out dates of ODSs for developing countries start in 1999 for CFCs and a few years later for other substances. Therefore the base level to which the controls refer also lies at least partly in the future. This is especially significant for the consumption of HCFCs in developing countries, where no control measures apply until 2016 and the consumption is

allowed to grow until then. This could increase the upper limit, although it is very unlikely to happen.

Second, the emission of carbon tetrachloride is taken to be proportional to the production of CFC-11 and CFC-12 and is therefore calculated as a fixed percentage of that production. The emission thus calculated is approximately one-third of the maximally allowed production (or emission) (UNEP, 1994b).

Third, there are uncertainties in the rates of release of ODSs to the atmosphere. In the scenarios the emissions are calculated as a fraction of the bank. This fraction is based on an analysis of the quantities present in, and emitted from, the banks over the years 1990-1995. The release fractions for the substances are held constant from 1996 to 2100. Destruction or changes in the use of ODSs could change the estimated release fraction and thereby the emissions and shape of the equivalent effective stratospheric chlorine (EESC) curve. The integrated EESC value discussed in Section 11.4.4 is not very sensitive to the release fractions chosen because the major part of the production and bank of the ODSs is released to the atmosphere before 2050. For the integrated EESC it is not important when the emissions occur; the ODSs that reach the stratosphere before the EESC value reaches the 1980 value (approximately 2050) contribute to the integrated value.

Fourth, the control measures apply to classes of substances (Annexes), several of which contain more than one substance. In these scenarios the distribution of the allowed production over the various substances of a class is based on the historic distribution and is assumed to stay the same in the future. A different distribution will only slightly affect the calculated EESC.

All these factors introduce uncertainties in the future emission scenarios and can affect the emissions possible within the current regulations.

11.3.8 Illegal Production

The emissions could also exceed the Baseline scenario if illegal production and illegal import/export occur. Illegal imports of CFCs are known to take place, for example, on the basis of custom interdiction reports. An estimated 10 ktonnes of CFCs are imported illegally into the European Union every year (C&I, 1997). The global amounts of ODSs may be significantly higher, with some estimates suggesting about 30 ktonnes per year. Future amounts and duration of such illegal production are uncertain. Illegal imports are equated to illegal production in scenarios F1 to F3 of Table 11-3.

These scenarios consider both low and high estimates for CFCs, i.e., 20 ktonnes per year for 10 years (scenario F1) or 40 ktonnes per year for 20 years (scenario F2), assigned to CFC-12 and CFC-113 in a 2:1 ratio. In the high-estimate scenario, the illegal production of CFC-12 amounts to 6% of the 1989 and 17% of the 1995 CFC-12 production. For CFC-113 these numbers are 5% of the 1989 and 30% of the 1995 production. Scenario F3 considers an illegal import of Halon-1211 of 2 ktonnes per year for 10 years. This 2 ktonnes corresponds to 12% of the 1989 production of Halon-1211 and 19% of the 1995 production.

11.3.9 Other Species

Emissions of methyl chloride are considered to be, for a large part, from biomass burning, with smaller emissions from industrial sources and the oceans (Section 2.2.4). Methyl chloride is not controlled by the Montreal Protocol. The atmospheric mixing ratio is approximately 550 parts per trillion (ppt) and there are no data suggesting a temporal trend in its atmospheric burden (see Chapter 2). No emissions of methyl chloride are therefore considered in the scenarios discussed in this chapter, but a fixed tropospheric mixing ratio of 550 ppt is used in the calculations. The contributions of other halocarbons, for example, methylene chloride (CH_2Cl_2), chloroform (CHCl_3), perchloroethene (C_2Cl_4), phosgene (COCl_2), dibromomethane (CH_2Br_2), bromoform (CHBr_3), and methyl iodide (CH_3I), to the stratospheric chlorine/bromine loading are ignored here because their contributions are expected to be small, and for several species no temporal trend is detected (see Chapter 2).

11.4 FUTURE CHLORINE AND BROMINE LOADING

11.4.1 Method of Calculating Equivalent Effective Stratospheric Chlorine (EESC)

The approach used here to relate emissions of various ozone-depleting substances to stratospheric ozone depletion is similar to that of Prather and Watson (1990) and previous assessment reports (WMO, 1992, 1995). The model adopted was used in WMO (1995) and described by Daniel *et al.* (1995), and it uses the equivalent effective stratospheric chlorine (EESC) concept. EESC is an index developed to represent the

potential damage that a given mixture of ozone-depleting substances could cause to stratospheric ozone. Because of the impact of transport and other processes that depend on atmospheric attributes such as aerosol loading and temperature, equivalent effective stratospheric chlorine loading should not be regarded as a perfect gauge of the expected future ozone response. Instead, EESC can be thought of as a primary stratospheric forcing mechanism with the attribute that increasing chlorine/bromine loading will tend to lead to decreased ozone amounts.

In this model, abundances of the various ODSs are given by

$$\frac{d[x]}{dt} = S_x E_x - \frac{[x]}{\tau_x} \quad (11-1)$$

where $[x]$ is the average tropospheric mixing ratio, E_x is the emission rate of species x obtained as described previously in Section 11.3, τ_x is the lifetime of x , and S_x represents a factor used to convert a unit mass of species x to an average tropospheric mixing ratio. The EESC is then calculated by

$$\text{EESC}(t) = \sum_{\substack{\text{Cl-containing} \\ \text{halocarbons}}} n_x f_x [x]_{t-\text{lag}} + \alpha \sum_{\substack{\text{Br-containing} \\ \text{halocarbons}}} n_x f_x [x]_{t-\text{lag}} \quad (11-2)$$

where n_x represents the number of chlorine/bromine atoms in halocarbon x , f_x represents the relative fractional chlorine/bromine release compared to CFC-11, lag is the average estimated transport time required for the halocarbon to travel from the troposphere to the stratosphere (taken here as 3 years), and α accounts for the relative impact of bromine compared to chlorine in destroying stratospheric ozone. The 3-year lag time for transport from the troposphere to the stratosphere agrees with midlatitude data of Figure 7-8 of Chapter 7. For the long-lived species (CFCs, halons, and carbon tetrachloride) the lifetimes of Table 13-1 of WMO (1995) were used. The lifetimes for HCFCs and methyl chloroform are given in Table 2-1 of Chapter 2. For methyl bromide a 0.7-year lifetime was used (see Chapter 2) and for HCFC-123 a 1.4-year lifetime (WMO, 1995).

There are two general categories of uncertainties concerning the use of Equation (11-2) as a method of comparing future halocarbon emission scenarios. The uncertainties in the first category relate to our ability to accurately calculate EESC from the quantities on the

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right-hand side of Equation (11-2). Primary contributors to this category are uncertainties in the fractional halocarbon release and in α (for bromocarbons). Although the fractional halocarbon release has been estimated from measurements (Pollock *et al.*, 1992; Daniel *et al.*, 1995), its variation with altitude and latitude could make the choice of a “best guess” somewhat uncertain. Because of the importance of lower stratospheric ozone loss to column trends at middle and high latitudes, the values taken for this chapter are consistent with estimates of fractional halocarbon release in the lower stratosphere. The values adopted in this chapter are identical to those in WMO (1995), many of which were determined from observations (Daniel *et al.*, 1995). Determining the value of α is also complicated by variations with altitude, latitude, and season in some cases. It is widely accepted that α is roughly 40-60 for Antarctic ozone loss (see, e.g., WMO, 1995). In line with Chapter 2 of this Assessment (see Table 2-6), we adopt a value of 60 for α in representing globally averaged ozone loss. In Chapter 2 a bromine efficiency factor (combination of fractional release and α) of 58 is used for methyl bromide, which corresponds to an α of 54. Such a difference in the value for α is well within the uncertainty range (see also Section 11.4.4.4). Furthermore, it should be noted that recent work (Danilin *et al.*, 1996) suggests that at high latitudes during winter the value of α may change in response to changing chlorine and bromine loading. Further work is necessary to determine if these results can be generalized to a globally applicable α value. In the previous Assessment (WMO, 1995) a value of 40 was used for α . The larger α value used here has only a small effect on the EESC. Additional uncertainties in the calculation of EESC involve the appropriate choice of an effective lag time as well as the choice of which gases to consider as contributing to EESC. From Chapter 2, it is clear that a single lag time is not appropriate throughout the lower stratosphere. Our choice of 3 years therefore implies that the inorganic halogenated compounds in part of the stratosphere will respond more quickly (smaller lag time) to changes in tropospheric halocarbon emissions and more slowly (larger lag time) in other parts of the stratosphere. In this chapter, except for methyl bromide, we have not considered any halogenated source gases with global lifetimes less than 1 year. Although shorter-lived gases could certainly contribute to stratospheric chlorine and bromine, an estimate would have to be made concerning the amount transported to the stratosphere

before they could be used in Equation (11-2).

The second category of uncertainty relates to the use of the equivalent effective stratospheric chlorine concept in analyzing future scenario options. As discussed in Section 11.1, a primary limitation of the EESC formalism is that it ignores all atmospheric changes (e.g., aerosol loading, stratospheric temperatures, etc.) that could affect stratospheric ozone other than the increase in chlorine and bromine loading. Another limitation relates to the use of a single globally averaged quantity (EESC) to represent a possible future evolution of stratospheric ozone depletion. Such an assumption ignores the fact that changes in chlorine and bromine will affect ozone differently depending on latitude, altitude, and season. Furthermore, Prather (1997) has pointed out that the stratospheric inorganic halogen loading arising from short-lived source gases like methyl bromide will not respond to changes in the tropospheric source gas concentrations according to the source gas lifetime, as would be suggested by the EESC formalism of Equation (11-2). While each of these criticisms illustrates imperfections in the application of EESC to describe future ozone depletion, EESC is a useful concept in comparing the differences between future halocarbon emission scenarios.

11.4.2 Future Development of Mixing Ratios

The temporal evolution of the average tropospheric mixing ratios calculated with Equation (11-1) is shown for the Baseline scenario in Figure 11-3. Several points should be noted in relation to this figure. First, the emissions of the Baseline scenario are defined for comparing the effects of different control measures, and therefore the mixing ratios shown in Figure 11-3 are not necessarily the most likely future values. Second, the scenario is based on classes of species, assuming that within each class the future partitioning of emissions among individual species will remain constant at the 1995 value. It is possible that future changes in the demand and use of the various compounds will affect the distribution of emissions within each class, so that different relations between the emissions and mixing ratios may result. Third, the scenarios are designed to compare the long-term effects of different additional control measures, not short-term changes in individual species. Fourth, the model used to calculate the mixing ratios from the emissions is a zero-dimensional (box) model, which by nature does not describe latitudinal,

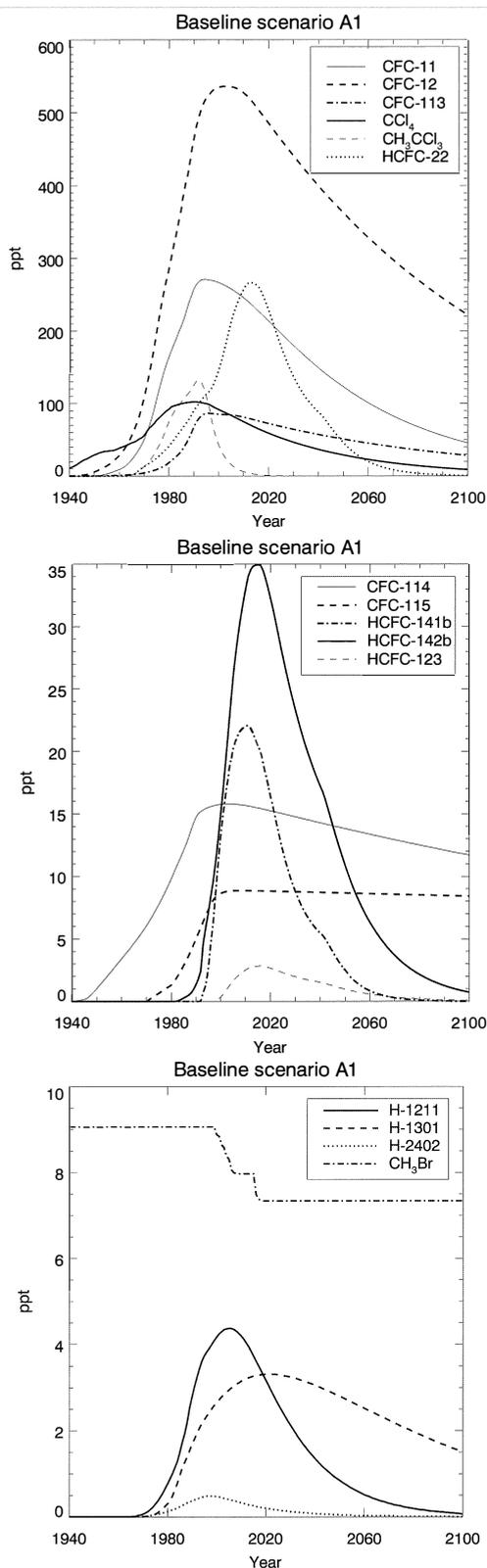


Figure 11-3. Temporal evolution of the average tropospheric mixing ratios of ODSs for the Baseline scenario (A1).

longitudinal, or vertical gradients in mixing ratios. The calculated values represent, therefore, a global average tropospheric mixing ratio and not a value at any specific location. Fifth, the time delay between production and release to the atmosphere is computed simply as a fixed fraction of the existing bank (the amount currently stored or being used in various applications). This fraction can change in the future, affecting the emissions and thus the concentrations of the species. From these considerations it is clear that the future evolution of the individual species as shown in Figure 11-3 should be viewed as representative but not necessarily an exact prediction. In particular, the precise year in which the mixing ratio of a species achieves its maximum value is quite sensitive to the above assumptions and should be viewed with some caution. The considerations discussed above hardly affect the time-integrated EESC that is used in Section 11.4.3 for comparing the different scenarios.

The evolution of concentrations, and hence EESC, of the ODSs is controlled by their lifetimes and emissions over time. For a few species the measured mixing ratios reached their maximum before or around 1996, e.g., CFC-11, CFC-113, carbon tetrachloride, and methyl chloroform (see Chapters 1 and 2). Partly because of their long lifetimes, CFC-12, CFC-114, and CFC-115 are expected to peak in the first decade of the 21st century. As discussed before, the future development of the HCFCs is more uncertain than of the CFCs. According to the Baseline scenario, the HCFCs are expected to reach their maximum value between 2005 and 2015. The evolution of Halon-1301 abundance is determined both by the atmospheric lifetime of 65 years and by the very slow release from the bank, i.e., the yearly emission is 4% of the amount in the bank (see also Butler *et al.*, 1998). According to the Baseline scenario, Halon-1211 and Halon-2402 will reach their maxima before 2010, whereas Halon-1301 will peak between 2015 and 2025. The short lifetime of methyl bromide causes its mixing ratio to respond rapidly to changes in the production and emission. The large natural emission determines the minimum value it can reach in the future.

11.4.3 Future Development of EESC

The equivalent effective stratospheric chlorine (EESC) is calculated using Equation (11-2) and the mixing ratios shown in Figure 11-3. The future evolution of the EESC (Baseline scenario) is shown in Figure 11-4. The maximum EESC is attained in the year 1997. Since the EESC is assumed to correspond directly and

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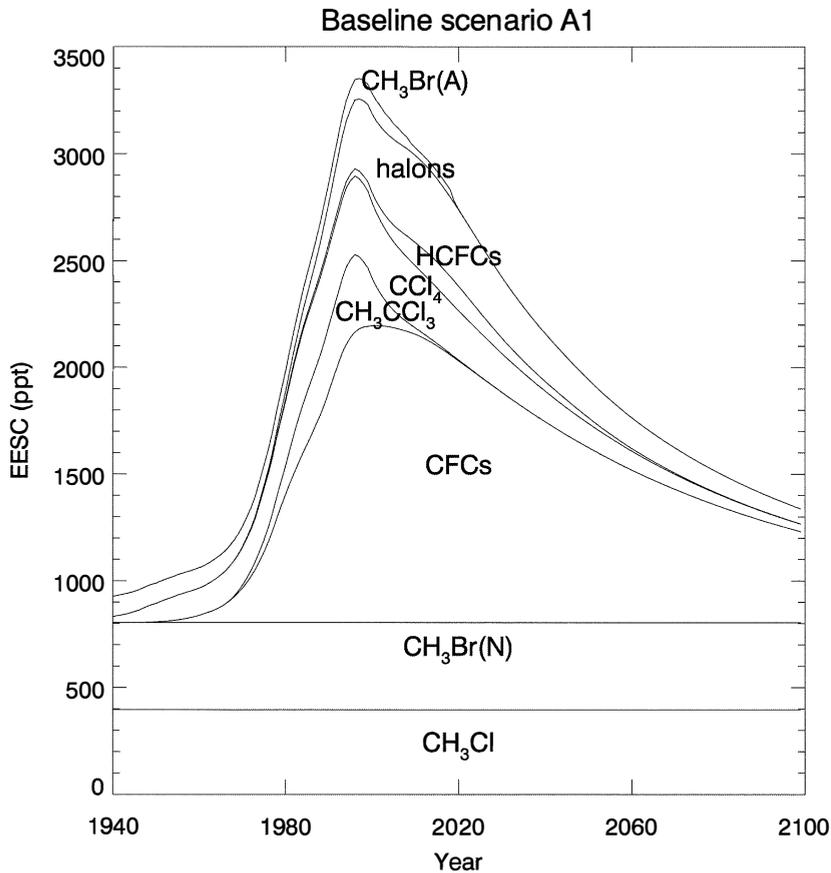


Figure 11-4. Contributions of the classes of substances to total equivalent effective stratospheric chlorine (EESC) according to the Baseline scenario (A1). Methyl bromide contributions from natural (N) and controlled anthropogenic (A) sources are shown separately.

linearly to the depletion of the ozone column, the maximum ozone depletion at midlatitudes is also expected to have occurred in 1997 (in the assumed absence of other natural and anthropogenic perturbations to ozone, and ignoring inter-annual and longer-term variability). After 1997, the ozone column amount is expected to begin gradual recovery. The expected rate of decrease of the EESC in the first half of the next century is 3 times slower than the increase in the 1970s and 1980s, i.e., -27 ppt/yr versus 81 ppt/yr.

In these calculations the ozone layer depletion is considered to be caused solely by active chlorine and bromine species. Other perturbations are ignored, such as changes in emissions of methane, nitrous oxide, and carbon dioxide; changes in stratospheric temperatures and aerosol loading; and aircraft emissions. The feedbacks stemming from ozone-related changes in tropospheric UV radiation and OH mixing ratios are also not taken into account in these analyses. Some of these effects are discussed in Chapters 10 and 12.

By far the largest contribution to the EESC comes

from the CFCs. In 1995, CFCs made up 41% of the total EESC (natural and anthropogenic emissions). The next largest anthropogenic contributions come from carbon tetrachloride (11%) and methyl chloroform (11%). The other species contribute less, i.e., halons 9%, anthropogenic emissions of methyl bromide 2.9%, and the HCFCs 0.9% (in 1995). The natural emissions of methyl chloride and methyl bromide make relatively large contributions to the EESC, 12% each. According to this Baseline scenario, the contribution of HCFCs will increase from 0.9% in 1995 to a maximum of 4% of the total EESC between 2015 and 2020, because of an increase in HCFC emissions and a decrease in the total EESC. The contribution of the halons is expected to increase from 9% in 1995 to a maximum of 13% in about 2010.

11.4.4 Effects of Control Measures

The effects of changing EESC levels on ozone are nonlinear and generally complex. Ozone measurements at midlatitudes and in Antarctica show that ozone

EESC: Scenarios 'A'

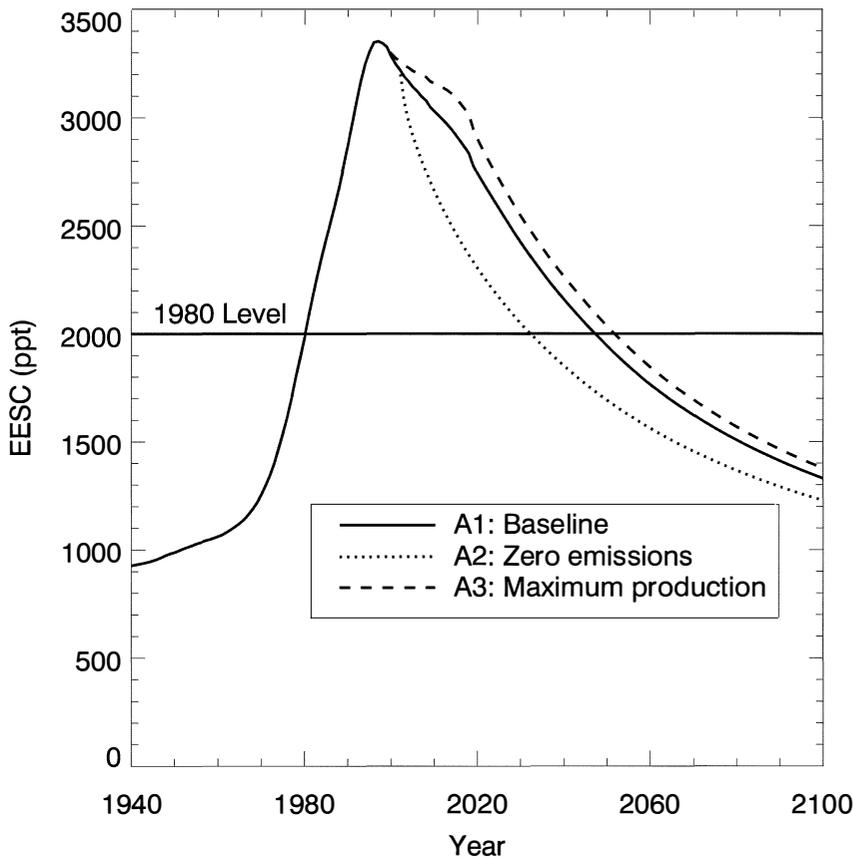


Figure 11-5. Equivalent effective stratospheric chlorine (EESC in ppt) for the Baseline (A1), Zero emissions (A2), and Maximum production (A3) scenarios.

depletion became observable in approximately 1980. For the purpose of comparing the impacts of different scenarios, 1980 is defined here as the reference year in which ozone depletion began, and the 1980 EESC value, 1.986 parts per billion (ppb) (see Figure 11-4), is considered as the threshold EESC level required for measurable ozone depletion. The same approach was used in WMO (1995). Any increments of EESC above the 1980 level are taken to result in ozone reductions, in proportion to the ozone/EESC trends observed between 1980 and 1990 (see Section 11-5 for details). If the EESC drops below the 1980 levels, ozone depletion is considered to cease, with the ozone layer returning to the natural background amount.

One useful measure of the impact of different future EESC reduction scenarios is the year (here termed year(x)) in which the EESC is expected to drop below the 1980 threshold and therefore complete ozone recovery is assumed to result. Another useful measure is the time-integrated EESC (ppt-year) from 1998

through the year(x) when the ozone depletion ceases. This quantity will be used to compare the effects of the different additional control measures. A third parameter is also defined as time-integrated EESC, but integrated from 1980 (rather than 1998) to year(x), to help evaluate the impact that ozone depletion may have on ecological systems over the whole period of ozone depletion. Similar definitions were used in WMO (1995). The three parameters defined here are shown in Table 11-6 for comparison of the different scenarios. Positive values indicate that the integrated EESC levels exceed that of the Baseline scenario. Negative values indicate the effect additional control measures may have on the integrated EESC. Figure 11-5 shows the EESC from 1940 to 2100 for the Baseline (A1), Zero emission (A2), and Maximum production (A3) scenarios, while Figure 11-6 shows the potential effect on EESC of the different scenarios relative to the Baseline scenario.

The results presented here differ from those given in the previous Assessment (WMO, 1995) because

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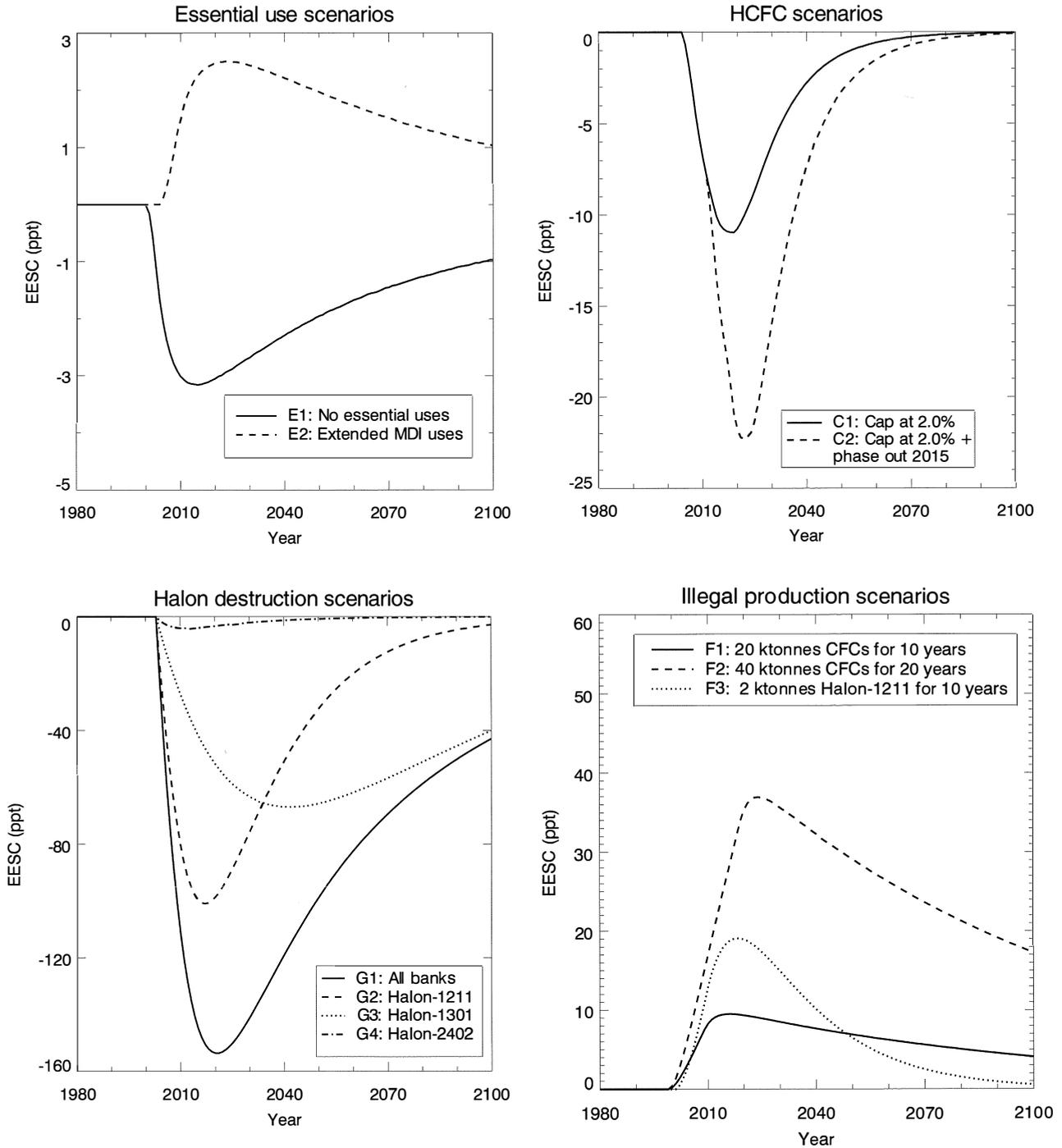


Figure 11-6. Change in EESC (ppt) relative to the Baseline scenario (A1) for the essential uses scenarios (E1 and E2), HCFC scenarios (C1 and C2), halon destruction scenarios (G1-G4), and illegal production scenarios (F1-F3). Negative values indicate that the scenario yields lower EESC values than the Baseline scenario (A1).

slightly different assumptions have been used for the Baseline scenario (A1). The most important difference is that in these scenarios we assume (in accordance with the Protocol) production of halons in developing countries, which was not considered in WMO (1995). The Baseline scenario therefore has a larger halon production than used in the previous Assessment. The production of CFCs in developing countries is also larger than in the previous Assessment. The assumption for this production in WMO (1995) was 10% of the total 1992 CFC production from 1996 to 2002 and decreasing to zero in 2006. In the current (1998) Assessment, this production is based on data from UNEP (1994b, 1997b); the amount is 20%-23% of the total 1992 CFC production from 1996 to 2004, decreasing to zero in 2010. The model used to calculate the mixing ratios and EESC values is the same as used before, but the parameterizations have been updated (i.e., new lifetimes for short-lived species and a factor of 60 for α ; see Section 11.4.1). A consequence of all the differences is that in the Baseline scenario A1, the EESC drops below the 1980 level in 2048, whereas this was 2045 in the previous Assessment (WMO, 1995). Because of uncertainties in the calculated values of alpha, we have examined the impact of a change in alpha from 60 to 80 on integrated EESC relative to the baseline scenario. This alpha change is larger than the expected uncertainty; it results in maximum decreases of a factor 1.1 for chlorine scenarios and maximum increases of a factor 1.2 for bromine scenarios.

Figure 11-7 shows the effect of completely halting production of CFCs, HCFCs, and methyl bromide ahead of the schedule specified by the current Protocol. Earlier termination of production yields larger reductions of integrated EESC, relative to the Baseline scenario. Among the three classes of compounds considered, the greatest benefit (i.e., largest EESC reduction) is achieved by an early stop in production of HCFCs and CFCs. For CFCs the avoidable production comes from developing countries, while for the HCFCs and methyl bromide it comes from both developed and developing countries. After a complete phase-out the change in integrated EESC is obviously zero. Figure 11-7 also shows the reduction in integrated EESC for each 1 Mtonne of avoided production, from which it is possible to estimate the benefits of partial reductions of allowed production.

11.4.4.1 MAXIMUM AND MINIMUM SCENARIOS

Under the Baseline scenario (A1) (Figure 11-5 and Table 11-6) the EESC level is expected to fall below the threshold level for ozone depletion (i.e., the 1980 level) in about 2048. According to the Protocol, CFCs, carbon tetrachloride, and methyl chloroform are still allowed to be produced in developed countries for use in developing countries (see scenario A3). If this production were to take place it would have a large effect on the future integrated EESC (Table 11-6): the threshold level would be reached about 4 years later.

With the Zero emission (A2) scenario, the threshold level is expected to be reached in about 2033. The Zero emission scenario, which assumes zero production of ODSs and prevention of any release to the atmosphere for all ODSs contained in existing equipment by the end of 1998, shows the lower limit of stratospheric chlorine set by the chemical and physical processes in the atmosphere, i.e., the lifetimes of the species.

11.4.4.2 CFCs AND CARBON TETRACHLORIDE SCENARIOS

Stopping the production of CFCs and carbon tetrachloride in all countries by 2004 (Figure 11-7 and scenario B3) may reduce the integrated EESC above the 1980 level by 2.5% over the next 50 years.

11.4.4.3 HCFC SCENARIOS

Developed countries must, since 1996, freeze their consumption of HCFCs at a level that is capped at 2.8% of their 1989 CFC consumption plus the 1989 HCFC consumption. A full phase-out must be achieved in 2030. Reducing the cap to 2.0% is expected to yield an integrated EESC above the 1980 level of about 0.8% less over the next 50 years (scenario C1, Figure 11-6 and Table 11-6). A phase-out of HCFCs in 2015 in developed countries, with additional interim reductions as given by scenario C2, will yield an integrated EESC above the 1980 level that is about 1.6% less. The year of re-attaining the threshold for ozone depletion is hardly affected by these additional HCFC control measures.

Since the HCFCs were included in the Protocol in 1992, the estimated lifetimes of most of these compounds, and hence the estimated impacts on ozone, have decreased by 15%-25%. This, in effect, reduces the calculated impacts of allowed emissions under the Protocol by approximately the same amount compared

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Table 11-6. Comparison of the scenarios: the year when EESC drops below the 1980 level and integrated EESC differences (relative to Baseline scenario A1).

Scenario	Year (x) when EESC is expected to drop below 1980 value	Percent difference in $\int_{1980}^x \text{EESC} dt$ above the 1980 level relative to scenario A1	Percent difference in $\int_{1998}^x \text{EESC} dt$ above the 1980 level relative to scenario A1
A1: Baseline scenario = Reference	2048	0	0
A2: Zero emissions	2033	-30	-42
A3: Maximum production	2052	+12	+18
A4: Zero production	2043	-14	-20
B3: Phase-out of CFCs and carbon tetrachloride by 2004	2047	-1.8	-2.5
C1: Reduce HCFC cap to 2%	2048	-0.6	-0.8
C2: Cap at 2% and phase-out HCFC in developed countries in 2015	2048	-1.1	-1.6
C3: Global phase-out of HCFCs by 2004	2047	-3.5	-5.0
D3: Phase-out of methyl bromide by 2004	2048	-0.9	-1.2
E1: No essential uses	2048	-0.3	-0.4
E2: Additional MDI essential uses	2048	+0.2	+0.3
F1: Illegal CFC production: low estimate	2048	+0.8	+1.1
F2: Illegal CFC production: high estimate	2049	+2.8	+4.0
F3: Illegal Halon-1211 production	2048	+1.2	+1.8
G1: Destruction of all halon banks in 2000	2043	-11	-16
G2: Destruction of Halon-1211 bank in 2000	2046	-7	-9
G3: Destruction of Halon-1301 bank in 2000	2045	-5	-7
G4: Destruction of Halon-2402 bank in 2000	2048	-0.2	-0.3
H1: No Protocol	Not reached	+659*	+938*
H2: Montreal Protocol (1987)	Not reached	+365*	+519*
H3: London Amendments (1990)	Not reached	+152*	+216*
H4: Copenhagen Amendments (1992)	Not reached	+15*	+22*
H5: Vienna Adjustments (1995)	2050	+3.5	+4.9

* Since the 1980 EESC level is not reached again, the integration is performed from the year 1980 (third column) or 1998 (fourth column), up to 2050.

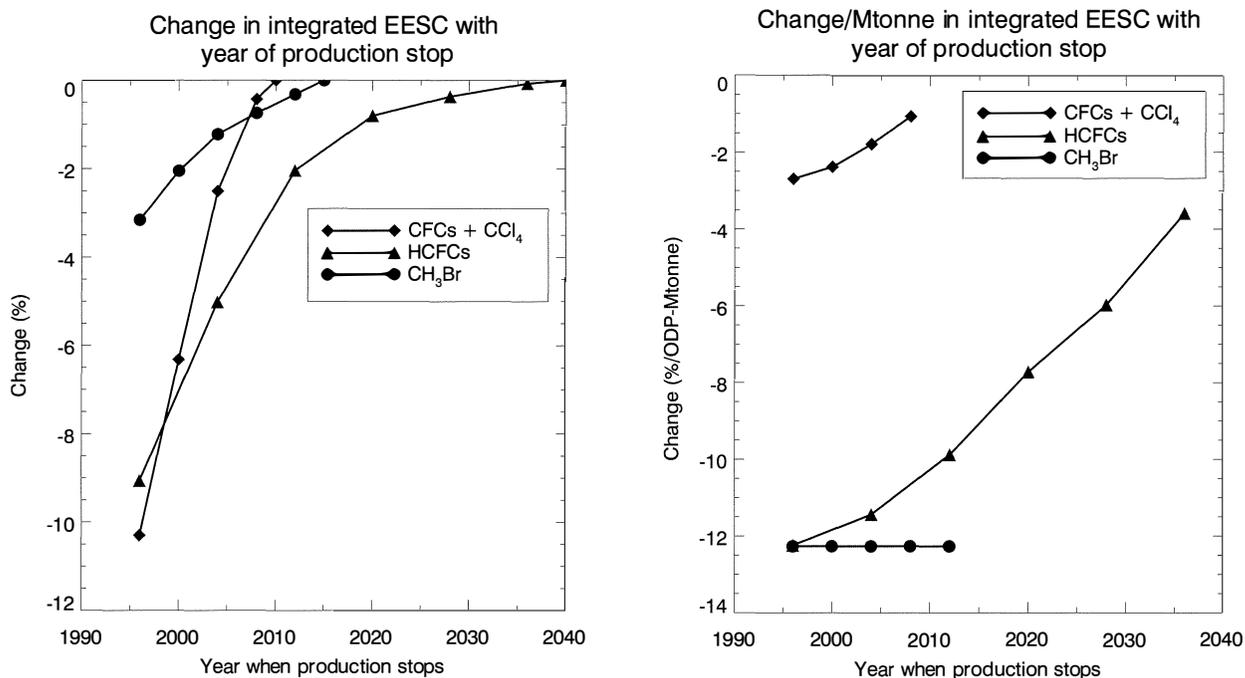


Figure 11-7. Percentage change (relative to the Baseline scenario) in integrated EESC above the 1980 level with a stop in production of CFCs, HCFCs, and methyl bromide in all countries in the year given by the horizontal axis. The integration is performed from 1998 to the year the EESC drops below the 1980 value. The right panel shows the percentage change in integrated EESC per avoided megatonne production (ODP-weighted).

with what was estimated when the limits were agreed on.

Stopping the production of HCFCs in all countries by 2004 (Figure 11-7 and scenario C3) may reduce the integrated EESC above the 1980 level by 5% over the next 50 years. The year of re-attaining the threshold for ozone depletion would hardly change. The effect of additional HCFC control measures for developing countries depends on the maximum amount they might produce in the future. The maximum allowed production is not defined; developing countries must freeze their HCFC consumption in 2016 at the level of 2015. If production is substantially more than assumed in the IS92a (IPCC, 1996) scenario, used as basis for the HCFC scenarios, the effects of additional HCFC control measures for developing countries would be larger.

11.4.4.4 METHYL BROMIDE SCENARIOS

Because of the short lifetime of methyl bromide, its atmospheric mixing ratio responds rapidly to control

measures. Moving forward the phase-out of methyl bromide from the current year of 2005 in developed countries and 2015 in developing countries to 2004 (Figure 11-7) may reduce the integrated EESC above the 1980 level by about 1% over the next 50 years (Table 11-6). The uncertainty about the budget of methyl bromide introduces uncertainties in the estimated effects of additional methyl bromide control measures. If a larger (smaller) fraction of the total sources than assumed in the scenarios used here were found to be of anthropogenic origin, and therefore potentially controllable under the Montreal Protocol, the effect of additional methyl bromide control measures would be greater (smaller).

11.4.4.5 ESSENTIAL USES SCENARIOS

The contribution of the currently (Montreal 1997) allowed essential uses (see Table 11-4) (UNEP, 1997a) of CFC-11, CFC-12, CFC-113, CFC-114, methyl

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chloroform, and Halon-2402 for the years 1996-1999 (methyl chloroform up to 2001) to the ozone depletion is very small; the integrated EESC above the 1980 level over the next 50 years would be 0.4% less if these essential uses were not allowed (scenario E1; Table 11-6). Conversely, extending the essential uses of CFCs for metered dose inhalers (MDI) for another 5 years (from 2000 to 2004, scenario E2) would increase integrated EESC above the 1980 level by 0.3% over the next 50 years.

11.4.4.6 HALON DESTRUCTION SCENARIOS

Current and future emissions of halons are expected to stem in large part from the amounts present in existing equipment. If newly produced halons and the halons currently contained in existing equipment were never released to the atmosphere (scenario G1), the integrated EESC above the 1980 level would be 16% lower over the next 50 years than with the current regulations (Table 11-6). The threshold for ozone depletion would be reached 5 years earlier. The destruction of Halon-1211 alone (G2), which might be technically more feasible, is expected to lower the integrated EESC above the 1980 level by 9% over the next 50 years. It should be recognized, however, that attempts at destroying halons may be accompanied by inadvertent partial releases to the atmosphere (UNEP, 1998a). If only part of the halon banks can be destroyed, the effect on the integrated EESC can be easily estimated as a fraction of the total effect.

11.4.4.7 ILLEGAL PRODUCTION SCENARIOS

The effect that illegal production of ODSs may have on the future ozone layer is shown by scenarios F1 to F3 (Figure 11-6, Table 11-6). A low estimate of illegal CFC production (a total of 20 ktonnes per year of CFC-12 and CFC-113 for 10 years in a 2:1 ratio) is expected to increase the integrated EESC above the 1980 level by 1.1% over the next 50 years, while the high estimate (40 ktonnes per year for 20 years) gives an increase almost four times larger, of about 4.0%. Illegal production of halons can have a significant effect on the integrated EESC, because of their larger potential for ozone depletion. For example an illegal production of 2 ktonnes per year of Halon-1211 for 10 years (scenario F3) is expected to increase the integrated EESC above the 1980 level by about 1.8%.

11.4.4.8 COMPARISON OF THE SCENARIOS

In Figure 11-8 the possible additional control measures (from Table 11-6) are ordered according to the potential effect they may have on the future ozone layer. Also shown are the estimated effects of illegal production of CFCs. Preventing emissions to the atmosphere of newly produced halons (H-1211 and H-1301) and of halons in existing equipment has the largest potential effect on the future ozone layer, followed by a faster global phase-out of HCFCs.

11.5 FUTURE OZONE AND UV RADIATION

The effects of different atmospheric release scenarios on future stratospheric ozone and surface UV radiation are best viewed in relative terms only, because many other uncertainties (e.g., atmospheric complexity, volcanic eruptions) tend to hinder strict prediction. The approach taken here is to use simple scaling relationships between EESC and ozone, and between ozone and UV radiation, based on two fundamental assumptions:

1. that observed trends in total ozone are attributed to and correlated with the concurrent estimated EESC increase, and
2. that all other factors affecting ozone and surface UV irradiance are held constant.

The use of such empirical ozone-EESC correlations (Daniel *et al.*, 1995; Slaper *et al.*, 1996) avoids the well-known complexities of different modeling approaches, but clearly does not address possible interactions with a changing future environment (e.g., in relation to possible climate change; see Chapter 12). Furthermore, it assumes that the observed ozone trends have had a negligible contribution from long-term natural variability, which at present is poorly understood.

Spatial and temporal time scales of variability are progressively shorter for halogen loading, stratospheric ozone, and surface UV radiation. While EESC is defined as a global and annual average value, strong seasonal and geographical variations exist for ozone (both average and trends) and even more for UV-B irradiance. Therefore the EESC/ozone/UV-B scaling relations are developed and applied on a latitudinal and seasonal basis, from which annual integrals can then also be derived.

In examining future surface UV scenarios, it is crucial to recognize that different wavelengths exhibit widely different sensitivities to stratospheric ozone

Comparing scenarios

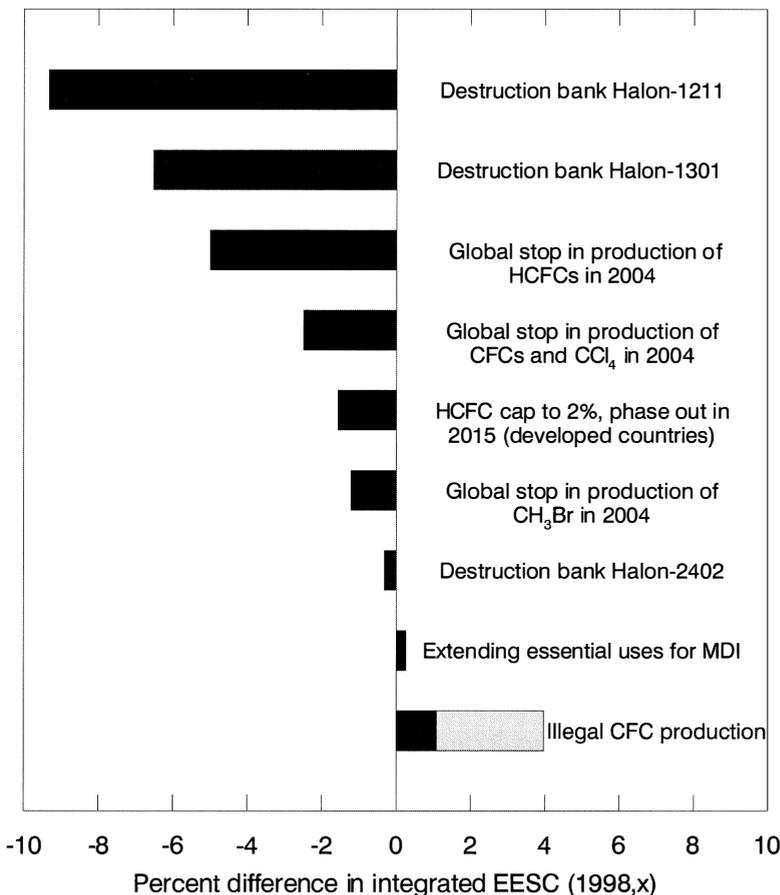


Figure 11-8. Percentage difference in integrated equivalent effective stratospheric chlorine (EESC) above the 1980 level (relative to the Baseline scenario) for future ozone layer scenarios. The integration was performed from 1998 to the year the EESC drops below the 1980 level (see Table 11-6). From top to bottom, the scenarios shown are: G2, G3, C3, B3, C2, D3, G4, E2, and F1/F2 (low and high estimates for illegal CFC production).

changes, because of the strongly varying ozone absorption spectrum. Ozone-UV scaling relationships are considered below both on a spectral basis, and for wavelength-integrated quantities weighted by spectral biological sensitivity functions.

11.5.1 EESC/Ozone Scaling

Stratospheric ozone reductions observed in recent decades are believed to have resulted from increasing levels of stratospheric halogens (see Chapter 7). Here, we assume that future ozone levels, associated with the emission scenarios of the previous section, will likewise be determined by stratospheric halogen loading, expressed in terms of equivalent effective stratospheric chlorine (EESC).

A simple linear representation of the effect of changing EESC levels on the ozone column (O_3 , in Dobson units (DU)), relative to 1980 levels, is given by

$$O_3(t) - O_3(1980) = \frac{A}{B} [EESC(t) - EESC(1980)] \tag{11-3}$$

where A is the ozone trend (e.g., DU per decade), and B is the EESC trend during the same time period (e.g., in ppb per decade). Historical data for EESC were given in Section 11.4. The increase during the 1980s is estimated as 0.861 ppb/decade, based on a 1980 reference value of 1.986 ppb and a 1990 value of 2.871 ppb. Following Daniel *et al.* (1995) we assume a threshold 1980 EESC value, so that $O_3(t) = O_3(1980)$ for $EESC(t) \leq 1.986$ ppb.

This simple relation is expected to fail for large ozone changes, e.g., in the Antarctic where saturation of ozone loss is observed, but should hold reasonably well at midlatitudes where relatively smaller ozone changes result from most of the scenarios considered here.

Values of the 1980 reference ozone and the ozone trend (A in the above equation) were taken from

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Table 11-7. Latitudinal dependence of annually averaged ozone, ozone trends, and ozone/EESC scaling factor, s (Equation 11-5).

Latitude, deg	O ₃ (1980), Dobson units	Trend, % per decade	Uncertainty in trend (2 sigma), % per decade	O ₃ /EESC scaling factor	Uncertainty (2 sigma) in O ₃ /EESC scaling factor
-55	346	-5.7	3.2	-0.126	0.070
-45	325	-4.0	2.6	-0.089	0.056
-35	297	-2.6	2.0	-0.058	0.044
-25	274	-1.1	1.9	-0.024	0.043
-15	263	-0.4	1.8	-0.009	0.039
- 5	267	-0.3	1.9	-0.007	0.042
5	269	-0.3	2.1	-0.007	0.046
15	266	-0.05	2.2	-0.001	0.048
25	279	-1.2	2.6	-0.026	0.058
35	311	-2.5	2.7	-0.056	0.059
45	350	-3.0	2.7	-0.067	0.059
55	371	-2.7	2.7	-0.059	0.060

measurements obtained by the Total Ozone Mapping Spectrometer (TOMS) version 7, as given by McPeters *et al.* (1996). Some interpolation was carried out to put all ozone data onto a common spatial and temporal basis (10° latitude bands, monthly). The trends were determined from data collected from November 1978 (the operational start of TOMS) through June 1991, after which the data may be influenced for several years by the Mt. Pinatubo eruption.

In the linear regime between threshold and saturation, Equation (11-3) can be rewritten in the form,

$$\frac{O_3(t) - O_3(1980)}{O_3(1980)} = s \left(\frac{EESC(t) - EESC(1980)}{EESC(1980)} \right) \quad (11-4)$$

where the scaling factor s is given by

$$s = \left(\frac{A}{O_3(1980)} \right) \left(\frac{EESC(1980)}{B} \right) \quad (11-5)$$

and expresses the percentage change in O₃ expected for a 1% increase in EESC. Table 11-7 summarizes the values used in the calculations, on the basis of annual averages. It should be noted that the ozone calculations were actually carried out at each latitude on a monthly

basis in order to obtain the correct seasonal cycle of ozone for use in the UV calculations described below, then normalized to the yearly changes shown in this table.

11.5.2 Ozone/UV Scaling

There is strong theoretical expectation and ample observational evidence (see Chapter 9) that decreases in atmospheric ozone enhance the UV radiation reaching the Earth's surface, if all other factors affecting atmospheric transmission are constant (e.g., clouds). Here, we estimate the changes in biologically effective UV radiation corresponding to the different scenarios of future emissions of ozone-depleting substances. These estimates are based on ozone changes alone, that is, without consideration of any possible long-term changes in cloud cover, tropospheric pollutants, or other factors affecting atmospheric UV propagation.

11.5.2.1 SPECTRAL IRRADIANCE

The spectral irradiance at the surface, $F(\lambda)$ where λ is the wavelength, is determined by the solar spectral irradiance incident at the top of the atmosphere and by the spectral transmission of the atmosphere. In particular, absorption by atmospheric ozone leads to strong attenuation of $F(\lambda)$ at wavelengths shorter than about

Sensitivity to -1% ozone change

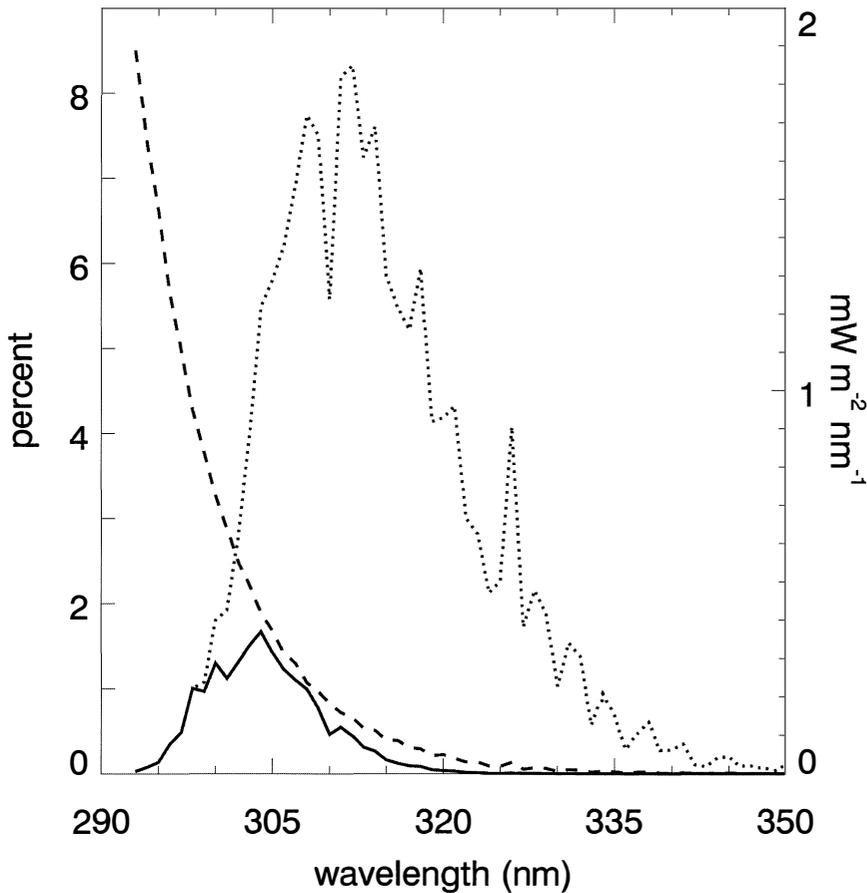


Figure 11-9. Spectral UV radiation changes for a 1% reduction in the total ozone column (from 300 to 297 Dobson units), for overhead sun. The dashed curve shows the percent increase in the spectral irradiance (left scale); the dotted curve shows the absolute change in spectral irradiance (right scale); and the solid curve shows the absolute change in spectral irradiance weighted by the erythemal action spectrum (right scale).

330 nm (see Chapter 9), with essentially negligible transmission near the short-wavelength side of the UV-B band (280-315 nm). Here, $F(\lambda)$ was calculated using a discrete ordinates radiative transfer model (Stamnes *et al.*, 1988) for cloud-free and aerosol-free conditions, 10% surface albedo, at 1-nm intervals over 280-400 nm (see Madronich *et al.* (1995) for additional details of the method). Although clouds and aerosols can attenuate UV radiation substantially, if assumed constant over the time of interest they have very little effect on the relative (percentage) changes in UV radiation stemming from stratospheric ozone depletion (WMO, 1990). Furthermore, zonally averaged UV trends estimated from TOMS satellite observations have been shown to be similar whether clouds are included or not in the derivation of the surface UV levels (Herman *et al.*, 1996).

The ozone-dependent UV increases are illustrated in Figure 11-9. A reduction in the column ozone leads to largest relative (percentage) increases in $F(\lambda)$ at the

shortest wavelengths (dashed curve), as has also been confirmed by observations (e.g., McKenzie *et al.*, 1991; Kerr and McElroy, 1993; Fioletov and Evans, 1997). However, the absolute spectral irradiance decreases rapidly at these wavelengths (due to ozone absorption), so that its largest increments are seen to occur at somewhat longer wavelengths, in the 300-330 nm spectral region (dotted line). It is these additional photons that raise concerns about environmental consequences of ozone depletion.

The wavelength dependence of UV changes must be considered in detail when estimating biological impacts, because higher energy (shorter λ) photons are frequently much more damaging to target biological molecules than longer wavelength (lower energy) photons. The relative sensitivity to different wavelengths (the so-called action spectrum) has been determined for a number of biological effects (see also Section 11.5.4). Here, we use the action spectrum for skin erythema

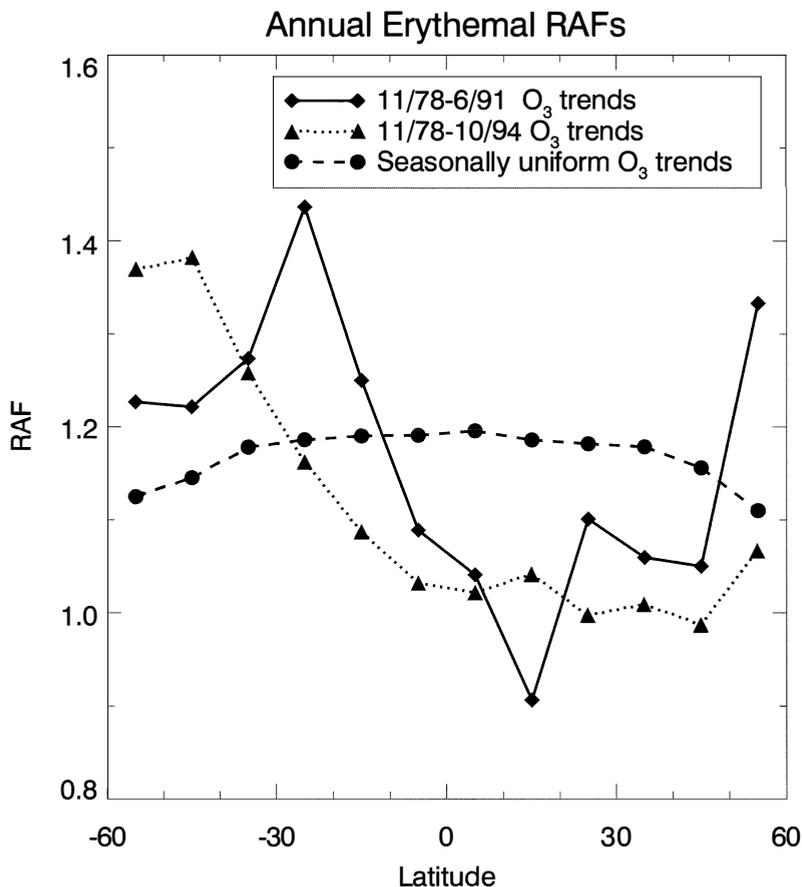


Figure 11-12. Latitudinal variation of the radiation amplification factor (RAF) for erythemal irradiance on an annual basis. At each latitude, values are computed from the detailed seasonal cycles of 1980 reference ozone, erythemal irradiance, and ozone trends (diamonds for trends for November 1978-June 1991; triangles for trends for November 1978-October 1994), or simply by assuming that ozone trends are uniform with season (circles).

variation expected if the ozone trend were applied uniformly (i.e., without seasonal dependence), with the residual latitude dependence arising solely from the prevailing solar zenith angles and average ozone levels characteristic of each latitude. For such seasonally uniform ozone changes, the annual RAFs are very similar to those obtained for instantaneous (monthly) erythemal doses shown in Figure 11-10.

11.5.3 Scenarios

Figure 11-13 shows the predicted changes in the annually averaged ozone column, and Figure 11-14 shows predicted changes in annually averaged UV_{ery}, at 45°S and 45°N for the Baseline, Zero emissions, and Maximum production EESC scenarios (A1, A2, and A3, respectively). The ozone changes are computed from the corresponding EESC scenarios using Equation (11-4) and the scaling factors given in Table 11-7 (e.g., at 45°N, a 0.067% ozone column reduction for each 1% increase in EESC above the 1980 level). The UV changes

are similarly computed from the ozone changes, using Equation (11-8) and the scaling factors (RAFTs) shown in Figure 11-12 (annual-based RAFs of ~1.05 at 45°N and ~1.22 at 45°S).

The time-evolution of ozone and UV radiation follows (by assumption) closely that of EESC, with minimum ozone (maximum UV_{ery}) in 1997 and return to 1980 levels in the years 2048 and 2033 for scenarios A1 and A2, respectively. At 45°N, the maximum reduction in the annually averaged ozone is expected to be about 15 DU, 4.3% lower than the 1980 value, leading to a maximum enhancement in the annually averaged UV_{ery} of about 4.7%. At 45°S, the ozone reduction and UV_{ery} increase are respectively 6.2% (about 20 DU) and 8.1%, in 1997 relative to the 1980 values. Seasonal patterns of these changes are expected (also by assumption) to follow those derived from TOMS ozone trends, e.g., with largest relative (percentage) increases in UV radiation occurring primarily during late winter and early spring in the Northern Hemisphere (see Figure 11-11) and more uniformly though the year in the Southern Hemisphere.

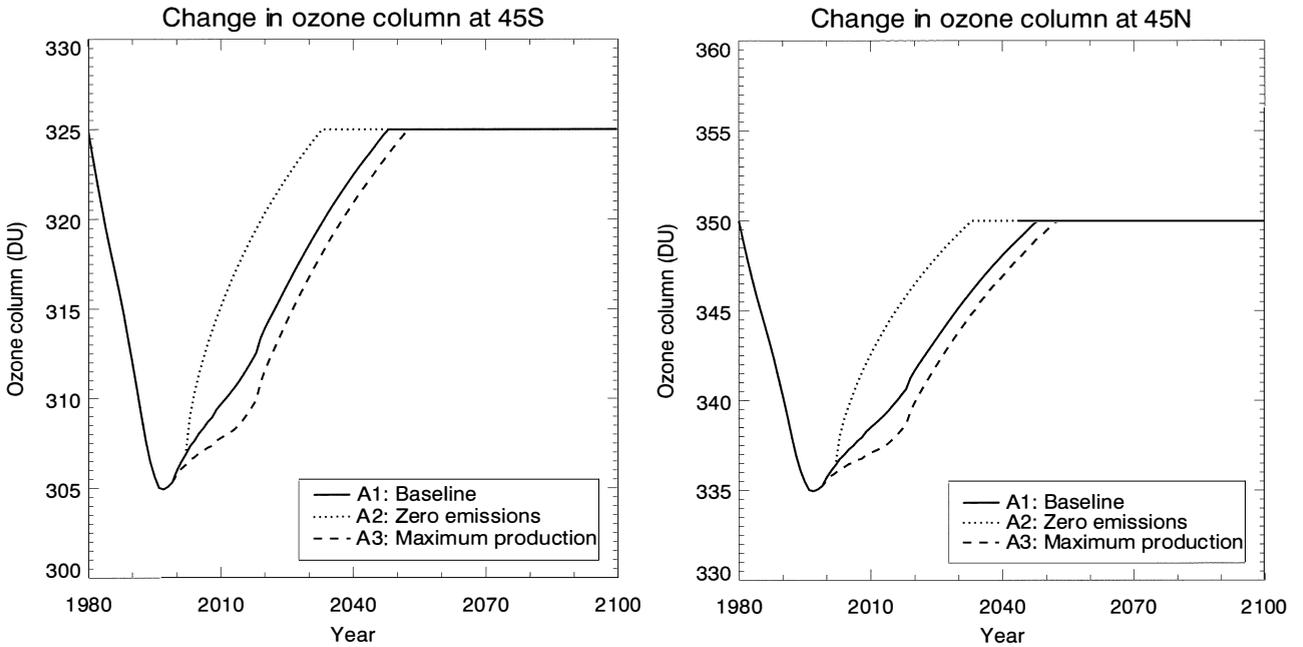


Figure 11-13. Changes in annually averaged ozone column amount at 45°S and 45°N, estimated from the EESC from the Baseline (A1), Zero emissions (A2), and Maximum production (A3) scenarios.

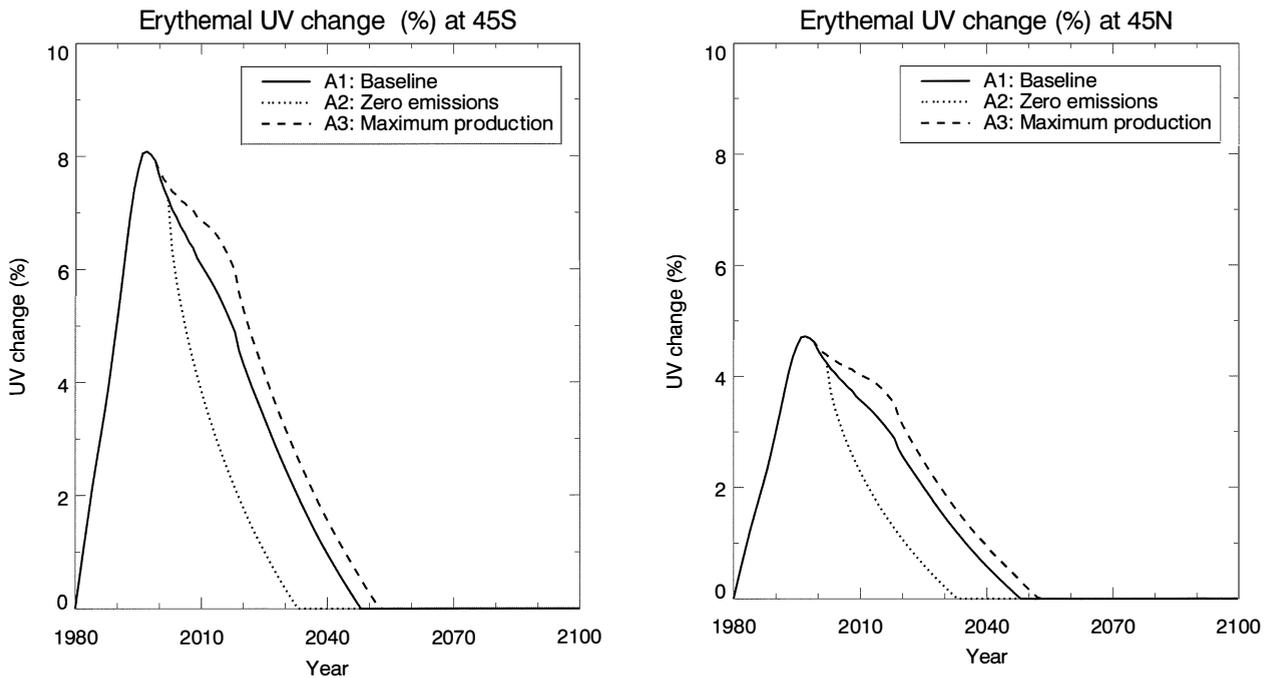


Figure 11-14. Changes (%) in annually averaged surface erythemal UV radiation at the Earth’s surface at 45°S and 45°N, estimated from the EESC from the Baseline (A1), Zero emissions (A2), and Maximum production (A3) scenarios.

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Table 11-8. Radiation amplification factors (RAFs)¹ at 30°N.

Effect	RAF	RAF
	January (290 DU)	July (305 DU)
Erythema CIE standard spectrum	1.1	1.2
Skin cancer in SKH-1 hairless mice (Utrecht)	1.5	1.4
SKH-1 corrected for human skin transmission	1.2	1.1
Generalized DNA damage	2.2	2.1
Damage to cornea	1.2	1.1
Damage to lens (cataract)	0.8	0.7
Occupational exposure limit	1.4	1.5
Generalized plant damage spectrum	2.0	1.6
Inhibition of photosynthesis, in Antarctic community	0.8	0.8
UV-A (315-400 nm)	0.03	0.02
UV-B (280-315 nm)	1.25	0.99
UV-B' (280-320 nm)	0.87	0.71

¹ Adapted from Madronich *et al.* (1995). RAFs computed on the basis of a daily integral.

CIE = International Lighting Commission (France).

UV-B, UV-B' give the results for two different ranges of UV radiation that are in common use.

Changes for other scenarios (which for the most part fall between the minimum and maximum cases) can be estimated by linear interpolation of the corresponding EESC values. Changes at other latitudes and on a seasonal (rather than annual) basis may also be estimated by direct application of the scaling factors (Table 11-7) for ozone and UV_{ery} .

11.5.4 Scaling for Other Biological Effects

The calculations presented so far have been based on the action spectrum for induction of erythema in human skin (McKinlay and Diffey, 1987), but it should be recognized that UV has many other effects on the environment. Impacts on tropospheric chemistry, for example, are discussed in Chapter 10 of this Assessment. Other effects include skin cancer induction, eye damage, immune system suppression, effects on animals and plants in terrestrial and aquatic ecosystems, and materials damage. Detailed discussion of these other effects is beyond the scope of this report (but see recent Effects Panel reports (UNEP, 1991, 1994a, 1998b)) except to note that each effect may have a different spectral sensitivity (action spectrum), and therefore a different scaling relationship to atmospheric ozone change. Some of these action spectra have been determined, and the

corresponding radiation amplification factors (RAFs) are shown in Table 11-8. For scenarios of reasonably small ozone change, the table may be used to translate UV_{ery} changes into changes in effective irradiance for another effect (x), via the approximate scaling relation

$$\frac{UV_x(t)}{UV_x(1980)} \approx \left(\frac{UV_{ery}(t)}{UV_{ery}(1980)} \right)^{\frac{RAF_x}{RAF_{ery}}} \quad (11-10)$$

An important consideration is that increases in UV exposure are not necessarily linked directly to effects. Complications may include long time delays between exposure and measurable effect (e.g., for the induction of skin cancer), competition changes within ecosystems, and possibly complex, multiple antagonistic and synergistic effects of UV exposure at the molecular level. More detailed discussion of the environmental effects of increased UV exposure is given in UNEP (1998b).

11.5.5 Uncertainties

The uncertainties in the calculation of long-term ozone changes from EESC changes are, necessarily, at least as large as the uncertainties in the estimates of the past ozone trends used to calibrate the EESC-ozone

relationship (see McPeters *et al.* (1996) for a discussion of these uncertainties). An additional but unquantified uncertainty arises from the assumption that the observed trends can be attributed quantitatively to EESC increases, thus neglecting possible offsetting or supplemental contributions from other long-term changes (e.g., climate change). Some additional minor uncertainties are introduced by the use of a simple linear correlation (Equation 11-3) and the saturation/threshold assumption, but these are unlikely to be very large for the small ozone changes considered here.

The relationship between surface UV irradiance and atmospheric ozone is well established for clear skies, but obviously many other factors not considered here (such as clouds, tropospheric pollutants, and surface reflections) can affect local UV levels quite significantly. To the extent that relative (percentage) changes in UV radiation are of greatest interest, it was already shown (WMO, 1990) that the presence of such factors does not modify the ozone-UV scaling relationship, as long as they are held constant. The assumption of long-term constancy for cloud cover and pollutant levels is strictly not justified, but there is at present very little confidence in the magnitude and even the sign of their potential future changes. Pragmatically, and in order to consider the effects of ozone change in isolation, long-term variations in these factors are neglected here.

The use of a specific action spectrum (here mostly for erythema induction) allows a reasonable spectral weighting of the UV radiation at ozone-dependent wavelengths, but it should be recognized that action spectra determinations carry significant experimental uncertainties, generally neglect polychromatic effects, and are seldom obtained under realistic environmental conditions. Limitations on the use of action spectra have been discussed in recent Effects Panel reports (e.g., UNEP, 1991, 1994a).

11.6 CONCLUSION

The scenarios considered in this chapter have been based on current (Montreal 1997) regulations, with a majority of these alternate scenarios addressing additional steps to reduce ODS emissions. While the resulting changes in EESC (and therefore stratospheric ozone and surface UV irradiance) are non-negligible, it is useful to recognize what has already been achieved by the earlier agreements. Prather *et al.* (1996) contrasted a free market (no regulation) scenario, in which

atmospheric chlorine remains above the 1980 levels throughout the 21st century, with the projected effects of the 1992 Copenhagen Amendments, which lead to recovery by the middle of the next century. Slaper *et al.* (1996) included additionally estimates of ozone decreases, UV radiation increases, and increases in the incidence rate of skin cancers in northwestern Europe and the United States, based on scaling relationships similar to those used here (see Section 11.5).

Figure 11-15 shows the estimated effects of no regulation, the original 1987 Montreal Protocol, and the subsequent Amendments and Adjustments, on the equivalent effective stratospheric chlorine. The assumptions that go into these extreme (and presumably avoided) scenarios are subject to considerably high uncertainties, and the calculated effects of the adopted control measures should be viewed as mere estimates. The assumptions about emissions (see Table 11-3, H scenarios) are similar to those used in the previous Assessment (WMO, 1995). The scenario without any Protocol (H1) assumes conservative annual growth of 3% for all ODSs and yields an effective chlorine loading of 17 ppb in 2050. The Montreal Protocol (1987) scenario (H2) reduces this projection to 9 ppb, by implementing a 50% reduction in the production of CFCs and a freeze in the production of halons in the developed countries. The London Amendments (1990) scenario (H3) further reduces the effective chlorine loading to 4.6 ppb in 2050, by phasing out the production of CFCs, halons, carbon tetrachloride, and methyl chloroform in the first decade of the 21st century in both developed and developing countries. In this scenario, it was assumed that the reduced production of these species would be compensated fully by an increase in the production of HCFC-22, so that the effective chlorine load increases again after 2050. The 1992 Copenhagen Amendments (scenario H4) limit the consumption of HCFC in the developed countries and yield an effective chlorine loading of 2.2 ppb in 2050. Because we assume in this scenario a 3% annual growth in HCFCs and methyl bromide in developing countries, the effective chlorine load increases again by the end of the 21st century. This increase is avoided by the control measures of the Vienna Adjustments (1995), scenario H5. The Amendments of Montreal (1997) reduce the effective chlorine load slightly further.

The effects of these different scenarios on integrated EESC above the 1980 level, relative to the Montreal 1997 scenario (A1) are shown in Figure 11-16.

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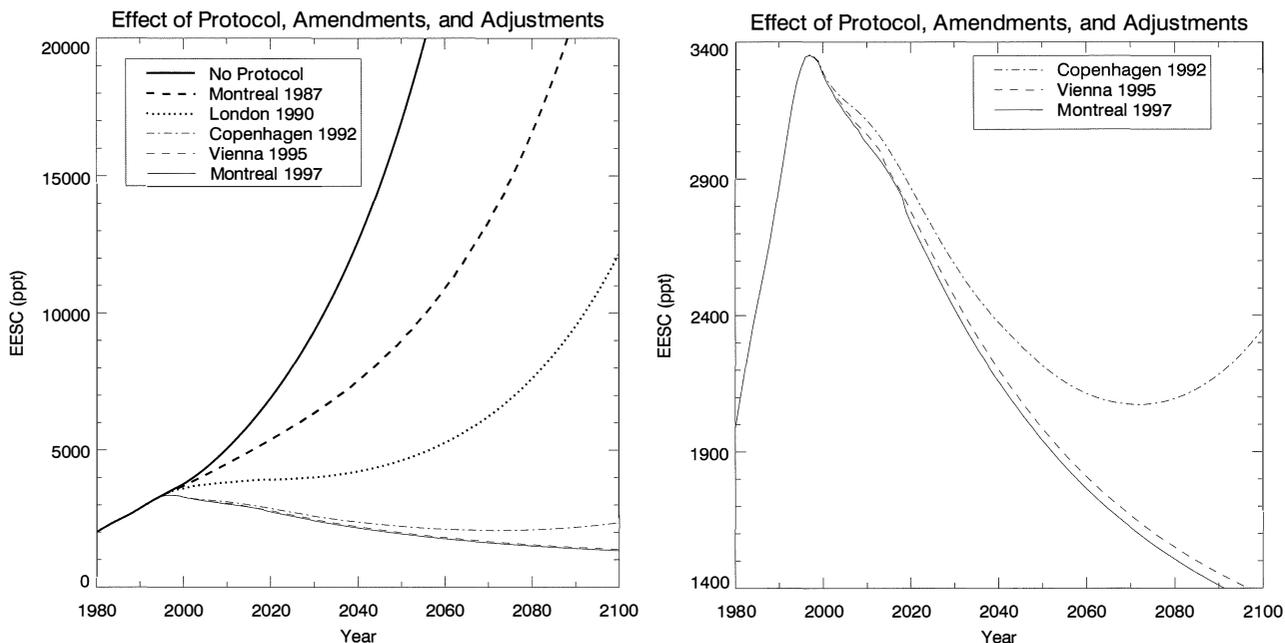


Figure 11-15. Estimated equivalent effective stratospheric chlorine represented by the various Amendments and Adjustments to the Montreal Protocol (scenarios H2-H5, A1), as well as a scenario with no international agreement on ozone-depleting substances (H1: No Protocol scenario: a 3%/year increase in production of CFCs, carbon tetrachloride, methyl chloroform, halons, HCFC-22, and methyl bromide). The more recent agreements are shown in greater detail for clarity.

The EESC increases for scenarios H1-H3 (No Protocol, Montreal 1987, and London 1990) are seen to be much larger than for the scenarios considered under the current regulations (compare Figures 11-8 and 11-16). The Adjustments of Vienna (1995), which limited the future production of methyl bromide, decrease the integrated EESC above the 1980 level by 17% (from +22% to +5%, relative to the current situation). An additional 5% reduction is achieved by the faster global phase-out of methyl bromide under the Amendments of Montreal (1997).

Figure 11-17 shows the increase in erythemal UV radiation at 45°N for the scenarios of No Protocol (H1) and scenarios of the Amendments and Adjustments to the Montreal Protocol. The method of calculation is similar to that described in Section 11-5, but was performed on a monthly (rather than yearly) basis to account for seasonally dependent saturation of ozone loss at the highest EESC levels (for details see Slaper *et al.*, 1996; Daniel *et al.*, 1995). The 3% per year growth assumed in the No Protocol scenario (H1) leads to more than doubling of the UV radiation by the middle of the next

century, while the Montreal 1987 and London 1990 regulations delay this doubling by about 30 and 60 years, respectively. Only under the Vienna 1995 and Montreal 1997 regulations are UV radiation levels expected to decrease from current peak levels, returning to near-normal levels by the middle of the 21st century. The potential impacts that such UV radiation increases would have had on the biosphere are discussed in the Report of the Panel on the Environmental Effects of Ozone Depletion (UNEP, 1998b).

The full sequence of calculations, from ODS emissions to stratospheric chlorine loading, to ozone depletion and increases in surface UV radiation, and ultimately to environmental and economic impacts, has substantial uncertainties at each step, as has already been discussed. The impacts of these uncertainties are reduced somewhat here by considering only relative (percentage) changes, e.g., for UV radiation, and by using simple scaling relations based on observations, e.g., satellite-derived ozone changes and their correlation with measured stratospheric chlorine loading. A more critical issue is the assumption that future stratospheric ozone

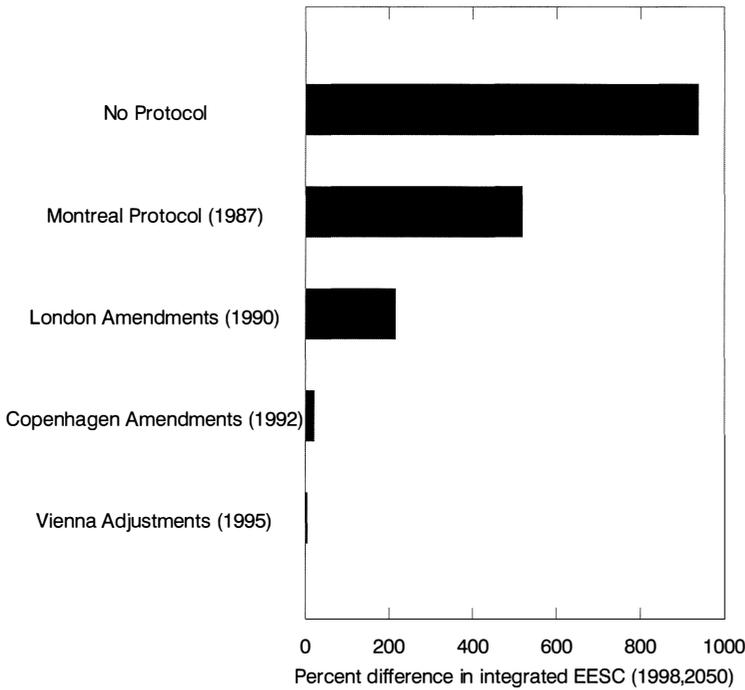


Figure 11-16. Percent difference in integrated equivalent effective stratospheric chlorine (EESC) above the 1980 level (relative to the Baseline scenario) of different Amendments to the Montreal Protocol (scenarios H1 to H5). The integration was performed from 1998 to 2050 (see Table 11-6).

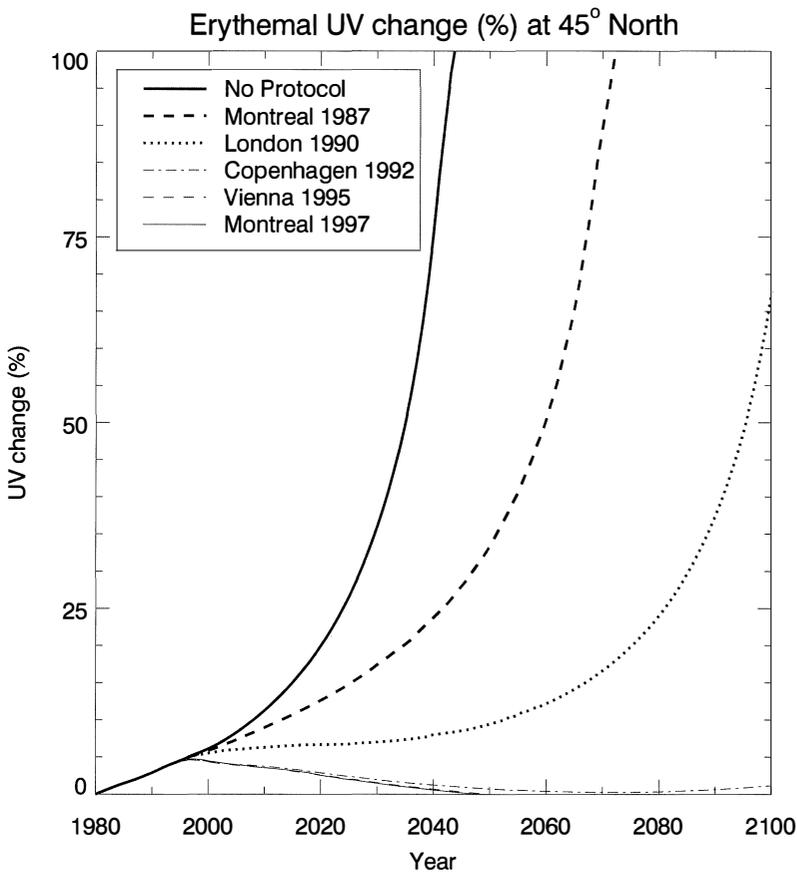


Figure 11-17. Estimated increase (%) in surface erythemal UV radiation at 45°N for the various Amendments and Adjustments of the Montreal Protocol (scenarios H2-H5, A1), as well as a scenario with no international agreement on ozone-depleting substances (H1: No Protocol scenario). Adapted from Slaper *et al.* (1996).

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will respond to halogen loading in much the same way as observed in the 1980s, assuming in essence that the future atmosphere will be in all other regards similar to that of the recent few decades. Other long-term changes in the global atmosphere are known to be occurring, in large part associated with human activities. In particular, strong interactions between tropospheric climate change and stratospheric ozone chemistry and dynamics have been identified, but they have not yet been quantified with confidence and continue to be a topic of active research (see Chapter 12). Thus, it is emphasized again that the calculations presented here are not intended as accurate predictions of future levels of stratospheric ozone or surface UV radiation, but are limited to the purpose of comparing the relative impacts of different future scenarios of ODS production and emission.

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