3.2. Ozone-depleting substances

International regulations have led to significant reductions in production, usage and emissions of ozone-depleting substances (ODSs), despite smuggling and illegal production, although large amounts of CFCs and halons are still in use; there is now a challenge to assist developing countries in meeting their commitments to phase out ODSs.

The total potential chlorine concentration in the lower atmosphere has decreased since its maximum in 1994, mainly due to the rapid phase-out of methyl chloroform, although the atmospheric concentration of halons is still increasing contrary to earlier expectations.

Increased levels of UV radiation will continue, with damaging effects for humans and ecosystems; full recovery of the ozone layer is unlikely before 2050.

There is some limited scope for additional measures to speed up ozone-layer recovery, mainly by eliminating global halon emissions.

Main findings

1. Depletion of the ozone layer

1.1. Total ozone decreased since 1980
Depletion of the stratospheric ozone layer, leading to increases in UV-B radiation, was initally a matter of scientific observation, but subsequently became the focus of pioneering initiatives for global environmental cooperation, as realisation grew of the dangers to human health and eco-systems (see EEA, 1998; Box 3.2.1; for an overview of current scientific understanding of ozone depletion, see European Commission, 1997, and WMO, 1999).

Damage to the ozone layer started in approximately 1980, and was initially observed in the polar regions. Satellite measurements show several years with very low total ozone values in the 1990s, but the rate of decline has slowed in recent years (Figure 3.2.1). The largest decreases in total ozone of 60-70% – known as the ozone hole – occur every year in spring over Antarctica (September-November); in 1998 the decrease in ozone in the Antarctic started earlier than usual (in mid-August) and reached a record size covering an area of 27 million km², the size of Europe. Since the beginning of the 1990s a similar phenomenon has been observed in the Arctic, with decreases of 30-40% in the ozone layer in spring (February – March) (Figure 3.2.2), although there is considerable year-to-year variability in the Arctic stratosphere. Very low ozone values occurred over the Arctic in the spring of

1993, 1996 and 1997. Higher values were recorded in March 1998, although these were still significantly lower than the values in 1980.

Ozone depletion is also seen, albeit to a lesser extent, in midlatitudes (25-60°). Between 1979 and 1991 there were downward trends in column ozone of 4.0%, 1.8% and 3.8% per decade, respectively, for northern midlatitudes in winter/spring; northern midlatitudes in summer/fall; and southern midlatitudes year round. The lowest values occurred in 1992 and 1993 exacerbated by the eruption of Mt. Pinatubo in the Philippines in June 1991. Since 1991 the linear trend observed during the 1980s has not continued, but rather total column

Percentage change in total ozone averaged over 60°S to 60°N	Figure 3.2.1
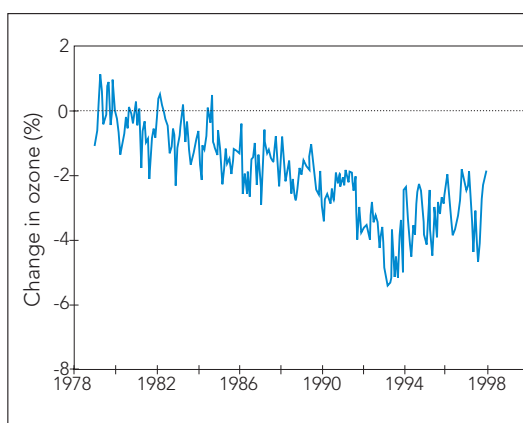
Note: Effects associated with the seasonal cycle (1 year), solar cycle (12 years) and the quasi-biennial oscillation (2 years) have been filtered out. The decrease in 1992-1993 is caused by the eruption of Mt. Pinatubo in 1991.

Source: WMO, 1999

Box 3.2.1. Background

Formation and destruction of the ozone layer
The stratospheric ozone layer is a diluted veil of ozone gas that stretches from about 10-40 km above the ground. The stratosphere contains approximately 90% of the ozone in the atmosphere, with the remaining 10% in the troposphere. Ozone is produced in the upper part of the stratosphere by short-wave radiation from the sun, while radiation with somewhat longer wavelengths and chemical reactions can dissociate it again, creating a dynamic balance between production and loss of ozone. Most of the ozone in the stratosphere is produced above the tropics where the sunlight is the most intense. Large scale circulation transports the ozone towards the poles causing a maximum in total ozone (the amount of ozone in a column that reaches from the ground to the top of the atmosphere) in the spring and a minimum in the late autumn.

Man-made chemicals are the cause of ozone depletion
Man-made ozone depletion is caused by chlorine and bromine, but not all compounds with chlorine and bromine affect the ozone layer to the same extent. A large number of compounds react with other gases in the troposphere and the halogen atoms are removed by rain and do not reach the stratosphere. The longer the atmospheric lifetime of a compound the more of it can enter the stratosphere. The chlorine and bromine compounds that cause significant depletion of the ozone layer are CFCs, carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), HCFCs, HBFCs and halons, all of which are completely of anthropogenic origin. They are used as coolant, aerosol propellant, cleaning agent, fire extinguisher, and in the production of foam insulation. The ozone layer can also be depleted by methyl chloride (CH_3Cl) which comes mainly from the oceans and methyl bromide (CH_3Br) which comes from natural and anthropogenic sources. Other substances such as nitrous oxide and and water vapour also participate in the process of ozone destruction.

The use of CFCs and halons, in particular, has led to an increase in the concentration of chlorine and bromine in the stratosphere. These compounds are chemically very stable and are not degraded in the troposphere. In the stratosphere they are dissociated by the short-wave radiation from the sun and release chlorine and bromine, which then take part in chemical chain reactions. A single chlorine or bromine atom can destroy many thousands of ozone molecules before being removed from the stratosphere. The natural balance between production and loss of ozone is therefore shifted towards a lower concentration of ozone.

Polar ozone depletion
The large depletion of stratospheric ozone in polar regions is caused by the combination of man-made chlorine and bromine compounds, extremely low temperatures and solar radiation. Reactions on the surface of polar stratospheric cloud (PSC) particles, which form at low temperatures, start a series of chemical reactions which cause a large destruction of ozone molecules in polar spring.

Other effects which can affect ozone depletion
Large volcanic eruptions, as from Mt. Pinatubo in 1991, can cause an extra depletion of ozone for several years.

Climate change may cause an increase in temperature in the troposphere and a decrease in the stratosphere. This may delay the recovery of the ozone layer in the Arctic and Antarctic, due to an increase in clouds in the stratosphere.

The greenhouse gases methane and nitrous oxide may affect stratospheric ozone by chemical interactions. This may have a positive or negative effect.

The impact of aircraft on the observed ozone depletion is unknown. The effect of a possible future fleet of supersonic aircraft flying in the stratosphere on the ozone layer could be slightly negative or positive, but should not exceed a few percent (Brasseur *et al.*, 1998).

Source: EEA, 1998; European Commission, 1997; Brasseur et al., 1998; WMO, 1999

ozone has been almost constant at all midlatitudes in both hemispheres since the recovery from the Mt. Pinatubo eruption. The observed total column ozone losses from 1979 to the period 1994-1997 are about 5.4%, 2.8% and 5.0%, respectively, for northern midlatitudes in winter/spring; northern midlatitudes in summer/fall; and southern midlatitudes year round. There are also considerable regional differences in ozone changes at midlatitudes. The largest midlatitude depletion occurs over Siberia in spring and Europe in winter and spring, while North America shows relatively smaller trends in winter and spring. In summer and autumn no significant trends are observed at midlatitudes. No trend in total ozone is seen over the tropics (EEA, 1998; WMO, 1999).

Ozone depletion shows a large year-to-year variability, due to instabilities in the air circulation in the Arctic stratosphere. The 1980 graph in Figure 3.3.2 shows a pattern typical of a non-depleted ozone layer. A similar depletion of stratospheric ozone is seen in the Antarctic since the beginning of the 1980s.

1.2. Ozone depletion is caused by man-made chemicals
The ozone layer has been damaged by the use of certain chemicals; if the damage is to be reversed, these uses must cease or substitutes developed. Anthropogenic emissions of chlorine and bromine compounds are the main cause of ozone depletion at midlatitudes and in polar regions (see Box 3.2.1). The impact of a substance on the ozone layer is determined by its ozone depletion potential and by its total emission to the
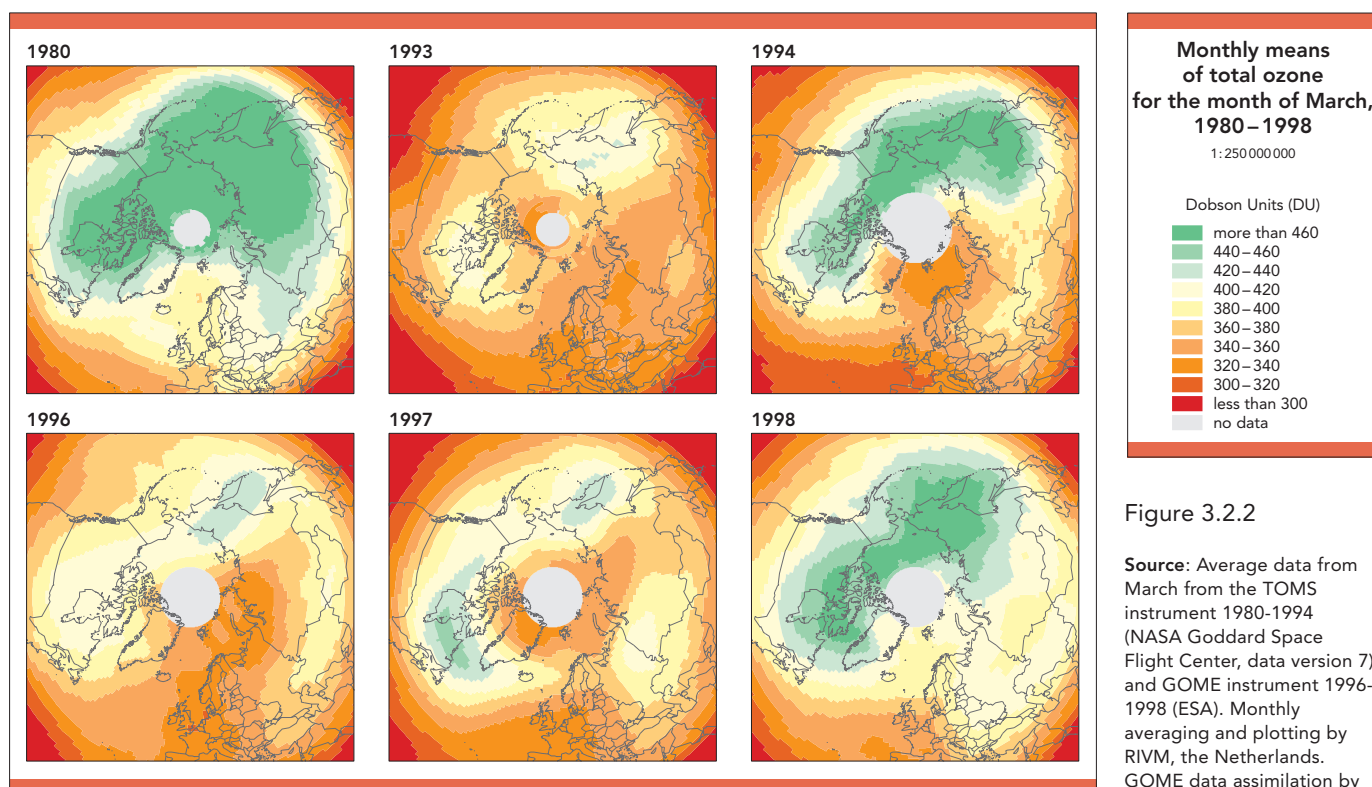
1980   1993   1994
1996   1997   1998

**Monthly means
of total ozone
for the month of March,
1980–1998**

1 : 250 000 000

Dobson Units (DU)

	more than 460
	440–460
	420–440
	400–420
	380–400
	360–380
	340–360
	320–340
	300–320
	less than 300
	no data

Figure 3.2.2

Source: Average data from March from the TOMS instrument 1980-1994 (NASA Goddard Space Flight Center, data version 7) and GOME instrument 1996-1998 (ESA). Monthly averaging and plotting by RIVM, the Netherlands. GOME data assimilation by KNMI, the Netherlands (Eskes *et al.*, 1999)

atmosphere. By far the largest contribution to ozone depletion comes from CFCs (WMO, 1999). In 1995 CFCs made up about 41% of the total effective chlorine+bromine in the stratosphere (natural and anthropogenic emissions). The next largest anthropogenic contributions come from carbon tetrachloride (11%) and methyl chloroform (11%). Other substances contribute less – halons about 9%, anthropogenic emissions of methyl bromide about 3%. Natural (non anthropogenic) emissions of methyl chloride and methyl bromide both contribute about 12%. HCFCs, used partly as substitutes for CFCs have a smaller effect (only about 1%), since they are largely dissociated and removed in the troposphere and only a fraction reaches the stratosphere. It should be noted, however, that CFC and its alternatives (HCFCs, HFCs) are greenhouse gases (see Chapter 3.1). The relative importance of the ODSs is expressed by their Ozone Depletion Potential (ODP). The ODP gives the impact (relative to CFC-11) of an emission of 1 kg of the substance on the depletion of stratospheric ozone (Table 3.2.1).

1.3. Progress with production and consumption of ozone-depleting substances (ODSs)

Global cooperation to protect the ozone layer has had considerable success in limiting production and consumption of damaging substances (see Section 3 below). Global production and emission of ODSs has

Ozone depletion potentials (ODPs)			Table 3.2.1.
Compound	**ODP**	**Compound**	**ODP**
CFC-11	1.0	HCFC-123	0.012 [2]
CFC-12	0.82	HCFC-124	0.026 [2]
CFC-113	0.90	HCFC-141b	0.086 [2]
CFC-114	0.85	HCFC-142b	0.043 [2]
CFC-115	0.40	HCFC-225ca	0.017
Halon 1301	12	HCFC-225cb	0.017
Halon 1211	5.1	Methyl bromide (CH_3Br)	0.37
Halon 2402	6.0 [1]	Methyl chloride (CH_3Cl)	0.02 [3]
Carbon tetrachloride (CCl_4)	1.20	CH_2ClBr	0.15 [3,4]
Methyl chloroform (CH_3CCl_3)	0.12	$CH_2BrCH_2CH_3$	0.026 [3,4]
HCFC-22	0.034	HFCs	<0.0005 [3]

The ODP is 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 HCFCs are partly used as alternatives for CFC; they have a lower ODP but are regulated by the Montreal Protocol. HFCs are also used as alternatives; their ODP is very small and they are not regulated by the Montreal Protocol.

Source: The latest scientific values from WMO (1999). The values differ slightly from the approved values used for regulatory purpose in the Montreal Protocol. 1) UNEP, Handbook for the Montreal Protocol (1996). 2) Value corresponding with the mostly used isomer. 3) Not regulated in the Montreal Protocol (WMO, 1999). 4) Wuebbles et al., 1998.

decreased sharply since the end of the 1980s as a direct result of international measures (Figure 3.2.3). Production and consumption in the European countries also show a strong decrease (Table 3.2.2 and Figure 3.2.4). (The following definitions are used in the Montreal Protocol (see below): Production = Amount produced minus what is destroyed, minus what is used entirely as feedstock; Consumption = Production plus import minus export. It is therefore possible to report a negative production or consumption.)

Production of CFCs in the major developed countries had declined by 1996 to about 7% of its maximum level at the end of the 1980s

as a result of the international regulations. HCFCs and HFCs, which are partly used as alternatives to CFCs, show an increase in production. HCFC-22 was already used in the 1970s in refrigeration and is used only partly as a substitute for CFCs. During the 1990s the production of ODSs decreased at a more rapid rate than that required under the Montreal Protocol. Production shown here is based on data from chemical companies in mostly western countries. The production in developing countries was much smaller in the past few decades but has increased in recent years relative to developed countries.

Emissions of ODSs lag behind their production by months, or years, depending on their use. In between emission and production the ODS is contained in the equipment in which it is used, the so-called bank. Large amounts of halons and also CFCs are still contained in existing equipment such as fire extinguishers, refrigerators and foams. If not recovered and destroyed these ODSs will, in time, be released to the atmosphere.

Consumption of CFCs has decreased significantly in all European countries, and particularly in western Europe. Total consumption in the EU in 1986 was seven times higher than in the Accession Countries, but by 1996 the difference was approximately a factor of two higher in EU15. Consumption of halons and methyl chloroform also decreased in all countries. However, HCFC

| Figure 3.2.3 | Large reductions in global production of CFCs; strong increase in HCFCs |
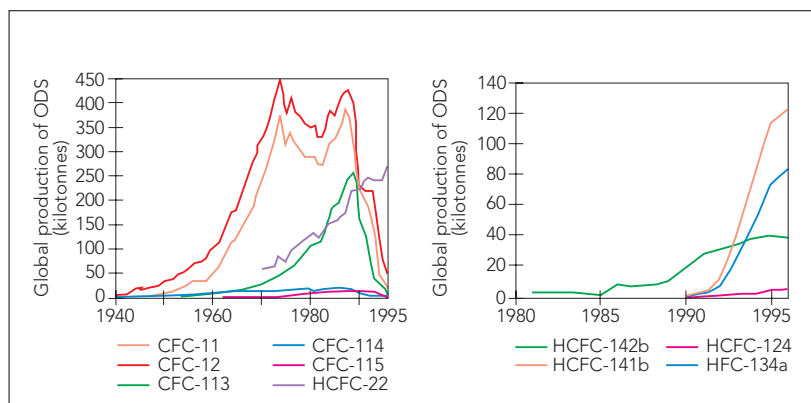
Source: AFEAS, 1998

| Table 3.2.2. | Production of ozone-depleting substances in the EU is largely decreased (ktonnes) |

Source: European Commission, DGXI. Data before 1995 from the EU12 countries only

Year	CFC-11	CFC-12	CFC-113	CFC-114	CFC-115	HCFC-22	Halons	CCl$_4$	CH$_3$CCl$_3$
1986	203.9	167.5	56.1	8.8	6.3	n.a.	13.78	n.a.	n.a.
1989	165.1	124.1	68.0	6.3	8.9	61.2	14.15	57.96	208.8
1990	116.9	93.0	62.4	4.2	7.9	69.2	11.63	29.34	214.7
1991	115.8	78.1	54.5	3.7	7.3	63.5	10.68	13.41	182.5
1992	101.1	78.8	39.8	2.4	8.4	76.0	6.81	11.42	182.4
1993	81.7	79.3	24.7	3.6	9.4	75.2	3.48	3.74	108.0
1994	28.8	41.7	10.6	1.8	7.5	86.7	0.00	2.50	83.6
1995	8.9	21.0	0.2	0.3	0.2	95.9	0.00	4.28	n.a.
1996	12.1	19.6	0.5	0.1	0.7	102.0	0.00	0.42	n.a.

Since 1994 halons are no longer produced in the EU as a direct consequence of the Montreal Protocol and its Amendments and Adjustments. The obligation of the Montreal Protocol was to phase out production of CFCs in 1996. The tighter EU regulations require a phase-out in 1995. From 1995 onwards a limited production of CFCs is allowed for essential uses as approved by the parties to the Montreal Protocol, and for use in developing countries.

n.a. no data available or no legal basis for data collection.
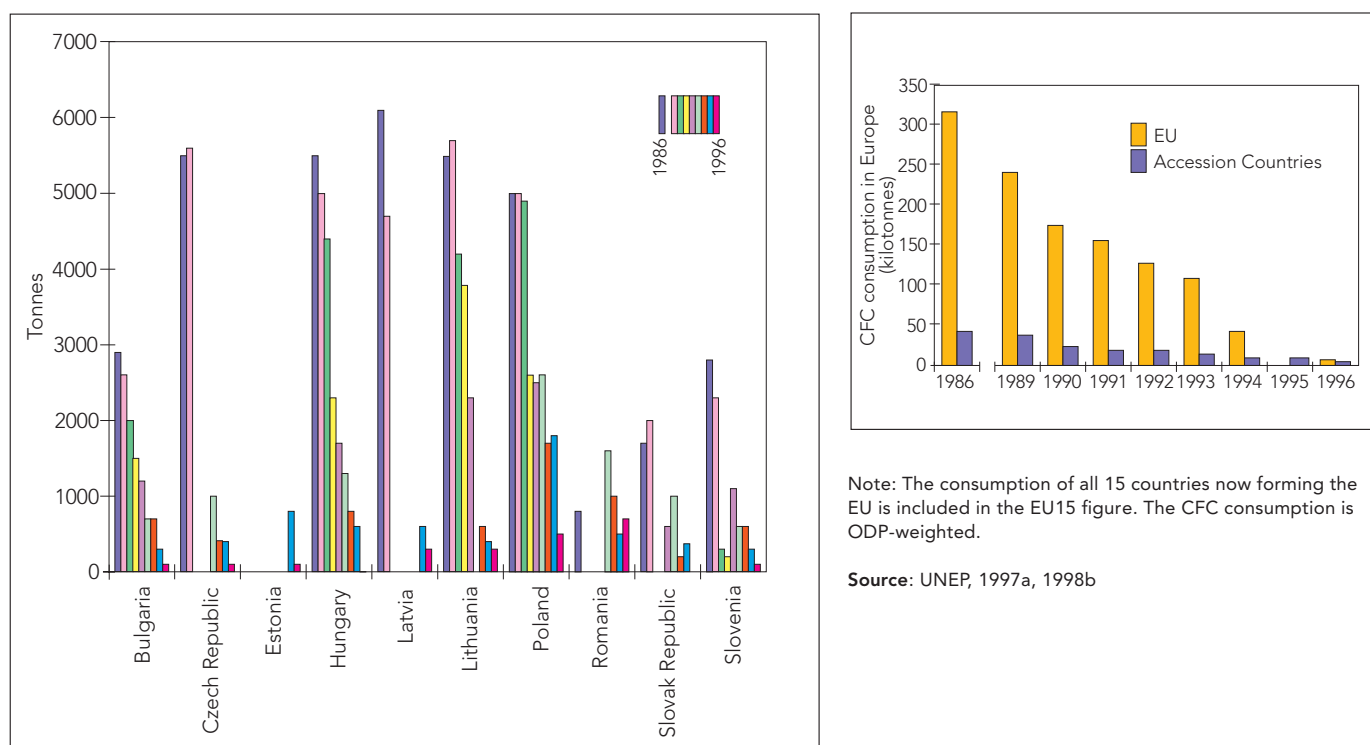
Note: The consumption of all 15 countries now forming the EU is included in the EU15 figure. The CFC consumption is ODP-weighted.

Source: UNEP, 1997a, 1998b

consumption, which is often used as a replacement for other ODSs, shows an increase in most countries.

1.4. Positive indications with remaining uncertainties

Measurements from ground-level monitoring networks show that the tropospheric concentration of major ozone-depleting substances (CFC-11, methyl chloroform and carbon tetrachloride) reached their maximum a few years ago and are now decreasing (Figure 3.2.5) (Midgley *et al.,* 1998; Simmonds *et al.,* 1998a). The concentration of CFC-12 is still increasing but the rate of increase has declined. The concentration of halons (the major anthropogenic bromine compounds used as fire extinguishers) is still increasing (Butler *et al.,* 1998). Whilst the production of halons was phased out in developed countries in 1994, the continuing increase in concentration is probably caused by emissions from halons in existing applications, mostly in developed countries and from newly produced halons in developing countries (SORG, 1996; WMO, 1999).

The total potential chlorine+bromine concentration, a measure for the total potential depletion of the ozone layer, reached its maximum in 1994 and is now declining. The atmospheric concentration of several HCFCs and HFCs, which are used to replace CFCs for refrigeration, foam and solvents, are shown to be rapidly increasing (Simmonds *et al.,* 1998b), although the concentrations are still low (below approximately 10 ppt).
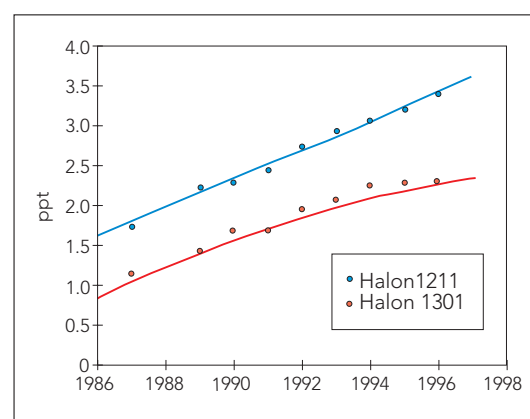
2. Action to protect the ozone layer

2.1 The Montreal Protocol

Measures to protect the ozone layer, beginning with the 1985 Vienna Convention, represent a pioneering global environmental initiative, establishing a system of world-wide regulation of production and use of the

The potential chlorine+ bromine is the sum of all chlorine and bromine atoms in the troposphere.

Source: ALE/GAGE/AGAGE (Prinn *et al.,* 1998) and NOAA/CMDL (Elkins *et al.,* 1998) networks.

chemicals which damage the ozone layer. The Montreal Protocol on Substances that Deplete the Ozone Layer (1987) established a schedule for the phase-out of CFCs and halons, and this was speeded up by the 1992 Copenhagen Amendments which also set limits on the production of HCFCs.

The current control measures in the Montreal Agreement (of September 1997), which is now awaiting ratification, are shown in Table 3.2.3. There are controls on the production and consumption of classes of ozone-depleting substances (CFCs, halons, HCFCs, HBFCs, carbon tetrachloride, methyl chloroform, and methyl bromide) and within a class, substances are weighted by their ozone depletion potentials (ODPs).

All EU Member States as well as the European Community and most of the Accession Countries have ratified the Copenhagen Amendments (Table 3.2.4), and consumption of ODSs in the remaining Accession Countries is in line with the Copenhagen Amendments (see Figure 3.2.4). In the Montreal Protocol and its amendments and adjustments the distinction is made with respect to the control measures, between developing and developed countries. Any developing country whose annual consumption of CFCs and halons is less than 0.3 kg per capita is entitled to a moratorium of 10 years to comply with the control measures required of developed countries. Romania and Slovenia are categorised as developing countries for the Montreal Protocol. In developed countries very limited production and consumption of ODSs is allowed for essential uses. Production is also permitted to meet the basic domestic needs of developing countries, up to a maximum of 15% of the base level production (of CFCs, carbon tetrachloride, methyl chloroform, halons and methyl bromide), defined as the production in a reference year (e.g. 1986 for CFCs in developed countries), to which all commitments apply. Developing countries must phase out CFCs, halons and carbon tetrachloride in 2010 and methyl chloroform in 2015. Regulation of HCFCs begins in 2016 with complete phase-out by 2040. The production of methyl bromide has to be frozen in 2002 and phased out by 2015.

The European Union Council of Ministers has adopted a common position on a proposed Council Regulation (Table 3.2.5) to set limits on the production of HCFCs (the Montreal Protocol only limits the consumption of HCFCs), to impose tighter controls on the consumption and use of HCFCs, and on the production and consumption of methyl bromide (European Commission,

Table 3.2.3.		Reduction and phase-out schedules of ODSs in developed countries

Compound	Year	Montreal Protocol
Halons	1994	100% phase-out
CFCs, carbon tetrachloride, methyl chloroform	1996	100% phase-out (phase-out of CFCs and carbon tetrachloride by 1995 in EU)
HBFCs	1996	100% phase-out
HCFCs	1996	freeze on calculated consumption at 2.8% of CFC consumption in 1989 plus total HCFC consumption in 1989 (calculated at 2.6% of CFC consumption in EU)
	2004	35% reduction from above freeze limit
	2010	65% reduction
	2015	90% reduction
	2020	phase out with a 0.5% tail until 2030 to service existing equipment (phase-out consumption by 2015 in the EU)
methyl bromide	1995	freeze on production and consumption at 1991 levels
	1999	25% reduction from above (25% reduction within 1998 in the EU)
	2001	50% reduction from above freeze limit
	2003	70% reduction
	2005	100% phase-out

1998). The sale and use of CFCs, halons, carbon tetrachloride, methyl chloroform and HBFCs would also be prohibited, tighter import and export controls are proposed for ozone-depleting substances.

The challenge facing developed countries and the EU is to assist developing countries in achieving their commitments. Several developing countries are reporting increased national consumption of ODSs in spite of various assistance programmes in effect.

2.2. Impact of methyl bromide on ozone layer still unclear

The Amendments to the Montreal Protocol of September 1997 established the first international regulation on methyl bromide (CH_3Br), specifying a schedule for the phasing out of its production (see Table 3.2.3). Methyl bromide has both natural and anthropogenic sources. When emitted, a large part is broken down in the troposphere. The rest reaches the stratosphere where the bromine is released and contributes to ozone depletion. The atmospheric concentration of methyl bromide is very low – between 9 and 10 ppt – with no observed trend. While the global budget of most ODSs is relatively well known, large uncertainties still exist in the sources and sinks of methyl bromide. Sinks are the different processes that remove the compound from the atmosphere or transform it into a different compound. The size of the identified sources and sinks (Table 3.2.6) are highly uncertain and the total identified sinks are much larger than the total identified sources. Identified sources thus constitute only about 60% of the identified sinks (WMO, 1999). Methyl bromide is now considered less important as an ozone-depleting substance than estimated at the time the Copenhagen amendment was negotiated. It is estimated that anthropogenic emissions of methyl bromide contribute about 3% to total ozone depletion, while natural emissions contribute about 12% (WMO, 1999). The ODP of methyl bromide is within an uncertainty range of 0.2-0.5.

Global production of methyl bromide was 62.5 ktonnes in 1996. The global use was 53.0 ktonnes, of which 12.9 ktonnes (24%) was within the EU. Only a small amount of this is produced in Europe, the rest is imported (Table 3.2.7).

2.3. The Ozone layer is expected to recover in the future

Full recovery of the ozone layer is expected to occur when the effective chlorine level in

Most European countries have ratified the Montreal Protocol and its Amendments (as of January 1999)			Table 3.2.4.
	Montreal 1987	**London 1990**	**Copenhagen 1992**
European Community + 15 MSs	X	X	X
Iceland	X	X	X
Liechtenstein	X	X	X
Norway	X	X	X
Bulgaria	X	X	X
Czech Republic	X	X	X
Estonia	X		
Hungary	X	X	X
Latvia	X	X	X
Lithuania	X	X	X
Poland	X	X	X
Romania[1]	X	X	
Slovakia	X	X	X
Slovenia[1]	X	X	X

(1) Commitments are under the category of Developing Country for the Montreal protocol.

Source: Update from UNEP, 1996

Tighter proposed controls in the EU			Table 3.2.5.
Compound	**Year**	**Commission proposal**	
CFCs, halons, carbon tetrachloride, methyl chloroform, HBFCs		Production and use prohibited	
HCFC production	2000	freeze at 1997 level	
	2008	65% reduction from 1997 level	
	2014	80% reduction	
	2020	85% reduction	
	2026	production prohibited	
HCFC consumption	1999	freeze on calculated consumption at 2.6% of CFC consumption in 1989 plus total HCFC consumption in 1989	
	2001	freeze on calculated consumption at 2.0% of CFC consumption in 1989 plus total HCFC consumption in 1989	
	2002	10% reduction from 2001 level	
	2003	65% reduction	
	2004	70% reduction	
	2008	95% reduction	
	2015	100% phase-out	
methyl bromide	1999	25% reduction of production and consumption from 1991 levels	
	2001	100% phase-out, with possible exemptions for critical uses	

Source: European Commission, 1998 COM (98)398

Table 3.2.6.	A best estimate of the global methyl bromide budget is not in balance (ktonnes/year)	
	Sources (range)	Sinks (range)
Ocean	56 (5 to 130)	-77 (-37 to -133)
Soils		-42 (-214 to -10)
Atmosphere		-86 (-107 to -65)
Gasoline	5 (0 to 10)	
Fumigation of soils, food and structures	41 (33 to 48)	
Biomass burning	20 (10 to 40)	
Totals	122 (48 to 228)	-205 (-358 to -208)

Source: Based on analysis of scientific data (WMO, 1999); the individual numbers have large uncertainty ranges. The net ocean flux ranges from -3 to -32 ktonnes/yr.

Table 3.2.7.	Reported production of methyl bromide in 1996 by country (ktonnes)
	Production of methyl bromide
US	26.87
Israel	23.68
Japan	5.02
France	4.46
Ukraine	1.40
China	1.10
Romania	0.018
Total	62.54

Source: Based on data reported by the countries to UNEP (1998b). Not all countries have reported all their data.

the stratosphere falls below the 1980 level of 2 ppb (the effect of the ODSs upon ozone depletion is measured in terms of 'effective stratospheric chlorine', which combines the effects of chlorine and bromine compounds in the stratosphere using the ozone depletion potential for each chemical). The effective stratospheric chlorine is expected to peak before the year 2000 (WMO, 1999) (Figure 3.2.6). The decrease from 2000 to 2020 is only by 10%. Consequently, the depletion effect will remain above the 1993 level for another 20 years.

Nevertheless, with the estimated future production of ODSs, and assuming full compliance of the latest Amendments to the Montreal Protocol, the ozone layer should start to recover. Full recovery will take at least another 50 years.

Based on past emissions and their projected trends, the total ozone minimum is esti-

mated to occur within the current or next decade (Figure 3.2.7: the calculations assume a -4.4%/decade trend in total ozone over Europe – see WMO, 1999, De Gruijl *et al.*, 1993; De Gruijl and van der Leun, 1994). Assuming that the observed loss in total ozone is due entirely to anthropogenic emissions, it can be expected that the minimum in total ozone and maximum change in surface UV will be reached in 1999. Interactions between ozone depletion and climate change, direct effects of greenhouse gases, changes in stratospheric temperatures and changes in aerosols and cloud cover can all affect the future ozone layer and surface UV radiation, and may result in a delay or acceleration of the recovery of the ozone layer.

In the coming two decades, the ozone layer is likely to be in its most vulnerable state. The temperature in the stratosphere has decreased over recent decades as a result of ozone depletion and increased levels of greenhouse gases. Continued high chlorine levels and low temperatures in the stratosphere could delay the recovery of the ozone layer, especially in polar regions (Shindell *et al.*, 1998).

With respect to future prospects, the baseline scenario shows the effective stratospheric chlorine assuming compliance with the latest amendments of the Montreal Protocol (see Figure 3.2.6). This scenario starts with the reported production of ODSs and applies the regulations for developed and developing countries separately. (For developing countries, the maximum production estimated by UNEP has been used – see UNEP, 1994b; WMO, 1999). Under this baseline scenario, full recovery would probably be reached by around 2050.

Recovery is brought forward in the 'Zero production' scenario. With a global cessation in production of all ODSs from the beginning of 1999, although certain emissions would still continue, effective chlorine+bromine levels would fall off at a faster rate. Full recovery would be expected in 2043.

The 'minimum' scenario portrays effective stratospheric chlorine trends assuming no emissions of any ODSs from 1999 onwards. It represents the lowest limit of effective stratospheric chlorine governed entirely by natural processes. This most favourable scenario provides an estimate of the earliest possible recovery year at about 2033.

In the 'maximum production' scenario full recovery is postponed to the maximum extent consistent with existing commitments. The Montreal Protocol allows a limited production of ODSs in developed countries after phase-out, to meet the basic domestic needs of developing countries. If this production were at the maximum level (15% of the 1986 base-level production for CFCs in developed countries), recovery would be delayed until about 2052.

There are of course many other possible scenarios, depending on the rate at which production and use of the various substances are phased out in developed and developing countries. This means that, for a specific date within the possible range, there can be trade offs between policy options.

Additional control measures should influence the future ozone layer, although by amounts generally smaller than already anticipated under current regulations. The largest potential beneficial effects may be attained by eliminating global halon emissions and HCFC production (WMO, 1999). Halons are used mostly in fire extinguishers and, although production in developed countries has stopped, large quantities are still present in existing equipment. When not destroyed, these quantities will eventually be released to the atmosphere. It should be recognised, however, that technical and economic factors make the destruction of halons difficult without inadvertent partial releases to the atmosphere (UNEP, 1998a). Absolute cessation of CFCs, carbon tetrachloride and methyl bromide production would provide smaller gains since production has already been greatly reduced, while smuggling of CFCs may adversely affect future ozone recovery.

2.4. Smuggling of CFCs may delay the recovery of the ozone layer

Since the prohibition of CFCs in 1996 (1995 in the EU), CFC smuggling has become a lucrative business, yielding enormous profits. CFCs are still allowed to be produced for use in developing countries and for some essential uses (e.g. metered dose inhalers for people with asthma). Illegal imports of CFCs, such as for air conditioners in cars, are known to take place for example on the basis of custom interdiction reports both in Europe and in the US. The NGO Environmental Investigation Agency (EIA, 1997) estimates that illegal trade in CFCs currently amounts to some 30 000 tonnes per year of which between 6 000 and 20 000 tonnes may occur
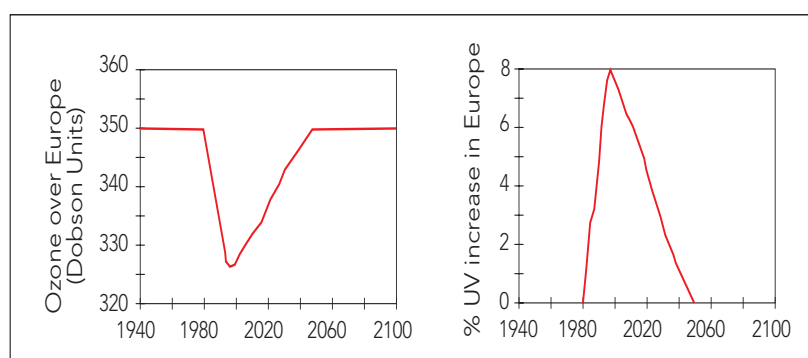
| Potential recovery of the ozone layer modelled | Figure 3.2.6 |

Source: WMO, 1999

Baseline
Minimum
Zero production
Maximum production
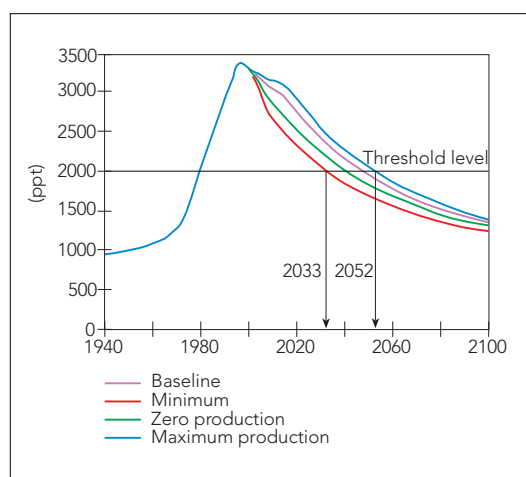
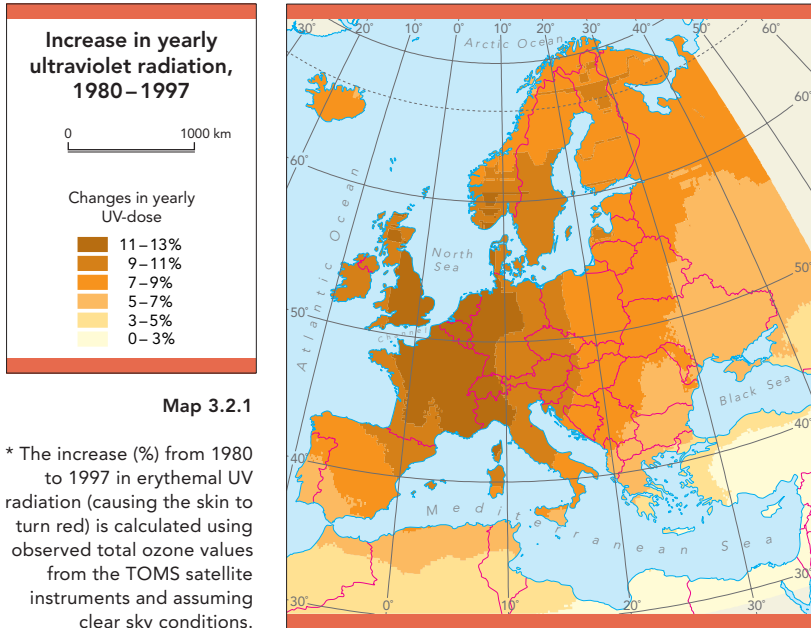| Good news for the future, but vulnerability in the short term | Figure 3.2.7 |

Source: The effective chlorine scenario is from WMO, 1999; the method of calculation is from Slaper et al., 1996.

in the EU; 30 000 tonnes equals 11% of the global production of CFCs in 1995. CFCs are still allowed to be produced (until 2010) in developing countries and in developed countries, for use in developing countries.

If continued at the current estimated rate, illegal CFC production will delay the recovery of the ozone layer by a few years. It may cause an increase in the UV related health and environmental effects comparable in size (but with opposite sign) to the latest revision of the Montreal Protocol in September 1997 (some additional limits on methyl bromide), but much smaller than what has already been achieved by previous Amendments of the Montreal Protocol (WMO, 1999). Illegal production and smuggling of halons, used in fire extinguishers, may cause more harm to the ozone layer due to its larger Ozone Depletion Potential (see Table 3.2.1), but the size of this production is highly uncertain.

Increase in yearly ultraviolet radiation, 1980–1997

0   1000 km

Changes in yearly UV-dose

- 11–13%
- 9–11%
- 7–9%
- 5–7%
- 3–5%
- 0–3%

Map 3.2.1

* The increase (%) from 1980 to 1997 in erythemal UV radiation (causing the skin to turn red) is calculated using observed total ozone values from the TOMS satellite instruments and assuming clear sky conditions.

Source: Update from Europe's Environment, EEA, 1998

| Figure 3.2.8 | **Long-term change in measured total ozone and erythemal UV radiation at Thessaloniki based on clear sky measurements at a solar zenith angle of 63°** |

Source: Zerefos *et al.*, 1998

| Figure 3.2.9 | **Montreal Protocol avoided a large increase in skin cancer** |

Source: Update from Europe's Environment, (EEA, 1998), with scenarios from WMO, 1999

No protocol
Montreal 1987
London 1990
Copenhagen 1992
Vienna 1995
Montreal 1997

3. The effects of ozone depletion

A thinning of the ozone layer will tend to increase the amount of UV radiation reaching the earth's surface (Kerr and McElroy, 1993; WMO, 1999). The result can be damage to human health, including skin cancer, eye cataracts, and suppression of the immune system. Marine and terrestrial ecosystems can also be affected by UV radiation (UNEP, 1994a), and there is evidence of reduced production of phyto plankton, the basis of the ocean's food chain, in the Antarctic during ozone hole conditions (Smith *et al.*, 1992).
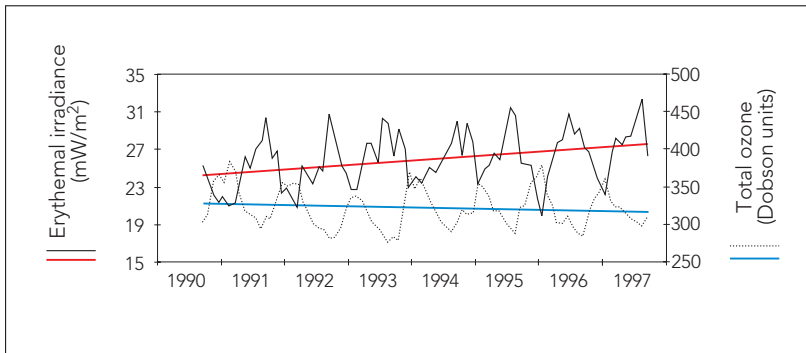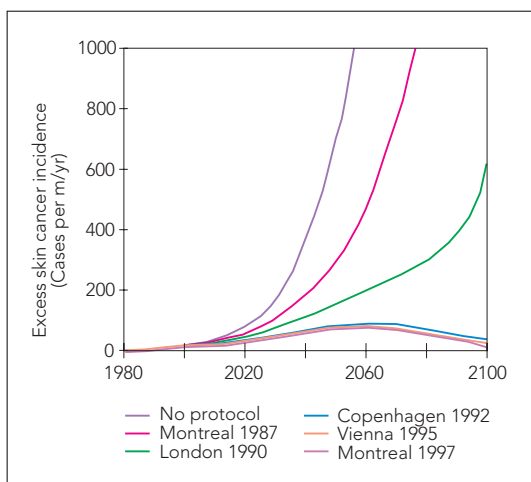
For Europe, the increase in UV is estimated to be largest over Northwest Europe (Map 3.2.1), associated with large depletion in total ozone (EEA, 1998). Deriving long term trends in UV radiation directly from measurements is difficult, due to the short time series and difficulties with calibration (WMO, 1994, 1999). Moreover, surface UV radiation is influenced by other factors, such as ozone in the troposphere, clouds and particles. Estimates from satellites show increases at northern mid-latitudes of 3-4% per decade and of 3-9% per decade for southern mid-latitudes (Herman *et al.*, 1996). UV increases of a few hundred percent have been observed under the Antarctic ozone hole in October (WMO, 1999).

Long-term measurements of UV radiation with high spectral resolution are scarce. One of the longest time series of spectral UV measurements is available from Thessaloniki, Greece. The data collected (Figure 3.2.8) shows a decrease in total ozone of 4.5%/decade from 1991 to 1998 accompanied by an increase in erythemal UV radiation of 19%/decade. It is estimated that about 4-5%/decade increase in UV radiation can be attributed to the observed change in stratospheric ozone and the rest to changes in other factors, for example the strong increase in local air pollution during the 1990s (Zerefos *et al.*, 1998).

International initiatives to protect the ozone layer are – thus far – a success story. The estimated benefits of the Montreal Protocol greatly exceed its costs (Box 3.2.2). In a hypothetical situation without the benefit of international regulations to protect the ozone layer, there would probably be a tremendous increase in skin cancer in the future (Slaper, *et al.*, 1996) (Figure 3.2.9). At present an incidence of about 1 100 cases

per million per year is estimated for North-west Europe. The total incidence of skin cancer could have quadrupled in Europe by the year 2100 with no intervention, or doubled with only the benefit of the original 1987 Montreal Protocol. Provided that the measures currently in force are fully implemented, the additional cases of skin cancer caused by ozone depletion will show a maximum of 78 cases per million per year around 2055. Thus, because of the time lags involved, skin cancer incidence is not expected to decline until about the middle of the 21st century.

Under the baseline scenario, additional accumulated cases of skin cancer in North-west Europe from now until the end of the 21st century are estimated at 5 000 cases per million (European Commission, 1999). With the maximum production scenario the estimate is increased by 600 cases per million people. In the event that global ODS production ceased in 1999, an estimated 600 cases per million of skin cancer could potentially be avoided in Northwest Europe. With zero emissions in 1999, this potential avoidance could reach 1400 cases per million.

Box 3.2.2. Benefits

Montreal Protocol benefits overwhelm the costs
The global benefits of the Montreal Protocol consist of health benefits (avoided cases of skin cancer, cataracts) and reduced economic damage to fisheries, agriculture and materials. Health benefits are not translated into economic benefits. The costs of implementing the Protocol involve the full range of costs associated with eliminating the use of ODSs. The costs are broken down in developed and developing countries. The estimated global costs and benefits extend over the whole range of ozone depletion (70 years). The excess skin cancer cases and associated fatalities will not stop when the ozone layer has recovered (around 2050) due to the long inhibition for skin cancer to develop.

Health Benefits (global)

Reduced cases of skin cancer	20 million
Reduced cases of cataract	130 million
Reduced skin cancer fatalities	335 000

Economic Benefits   400 billion euros

Reduced fisheries damage	52%
Reduced agricultural damage	42%
Reduced damage to material	6%

Costs   200 billion euros

	Developed countries	Developing countries
CFCs	31%	23%
Halons	5%	-
HCFCs	11%	3%
Methyl chloroform	17%	4%
Carbon tetrachloride (non feedstock)	2%	0.5%
Methyl bromide	3%	0.5%

Global net benefits are estimated at: 200 billion euros
(without health benefits)

The quantification of the costs and benefits has large uncertainty range and numbers should not be taken as definite.

Source: Environment Canada, 1997

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