

Greenhouse Gases: Interrelationship with stratospheric ozone depletion

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ABSTRACT

Emissions of greenhouse gases can affect the depletion of the ozone layer through atmospheric interaction. In our investigation the increase in emissions of chlorine- and bromine-containing compounds, largely responsible for the change in stratospheric ozone at mid-latitudes, was found to be -5.8% per decade from 1980 to 1990. The increase in CH₄ emissions in the same period changes this ozone trend by +1.4% per decade to -4.4% per decade, which is close to TOMS and Dobson measurements. The increase in N₂O emissions hardly affects this depletion. The decrease in stratospheric temperatures due to increased CO₂ emissions also diminishes the ozone depletion. The effect of these interactions in coming decades is to accelerate the recovery of the ozone layer. The trend in CH₄ emissions described in the business-as-usual scenario IS92a may yield 1980 ozone column levels in 2060 compared with 2080 with CH₄ emissions fixed at 1990 levels. The temperature decrease in the stratosphere may initially also accelerate the recovery of the ozone layer by several years, ignoring a possible large extra ozone depletion by the extra formation of polar stratospheric clouds over large areas of the world.

1. INTRODUCTION

Depletion of stratospheric ozone and the enhanced greenhouse effect are two major global environmental issues receiving a lot of attention from the scientific community, the public and policy-makers. Both phenomena are usually considered independently, initially a valid approximation. Destruction of ozone in the stratosphere is caused mainly by elevated levels of active chlorine and bromine compounds in the stratosphere, which arise mainly from anthropogenic emissions of chlorofluorocarbons (CFC's) and halons. The enhanced greenhouse effect arises from a changing radiation balance in the atmosphere caused by anthropogenic emissions from carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbons (CFC's). The stratosphere interacts with the greenhouse effect, or climate change processes, in several ways. Some anthropogenic emissions cause chemical changes in both the troposphere and stratosphere, thereby affecting the concentration of greenhouse gases in the troposphere and also influencing the amount of active chlorine and bromine compounds in the stratosphere. The enhanced greenhouse effect causes changes in temperature of both the troposphere and stratosphere, which may affect the chemical composition of the atmosphere as well as its dynamics. It may also influence the exchange processes between the troposphere and stratosphere and thus the chemical composition. Changes in stratospheric ozone also cause changes in the amount of UV radiation reaching the troposphere, which affects the photolysis rates of several chemical reactions and thus changes the chemical composition of the atmosphere.

The enhanced greenhouse effect, with its social and economic impacts, are under study in the international framework of the Intergovernmental Panel on Climate Change (IPCC, 1994; 1995). This forms an important basis for international negotiations on climate change. The scientific knowledge of the ozone layer is written down in WMO/UNEP reports, for example WMO (1991; 1994), and form the basis for discussions in the framework of the Vienna Convention and the Montreal Protocol. The atmospheric section of IPCC reports focuses on radiative forcing by greenhouse gases, while the WMO/UNEP reports mainly describe processes in the stratosphere. Both types of reports acknowledge interactions between the enhanced greenhouse effect and stratospheric

ozone depletion, but do not address them extensively. Here we will quantify the effects greenhouse gas emissions have on stratospheric ozone depletion and on the recovery of the ozone layer.

2. MODEL AND EMISSIONS

Chemical changes in the atmosphere are calculated with the RIVM version of the 2-dimensional model of the stratosphere (Velders, 1995a, 1995b) as originally developed by Harwood and Pyle (1980); see also Law and Pyle (1993a). Details of the simulations and emissions are given in Velders (1997). The basis for the future scenarios (1990-2100) were the IPCC IS92 scenarios (Pepper *et al.*, 1992). The CH₄ and N₂O emissions had to be changed slightly to be in agreement with the current concentrations. The future scenario used for the CFC's in all simulations was IPCC case 6 which closely resembles the Copenhagen amendments to the Montreal Protocol.

3. RESULTS OF THE SIMULATION

The concentration of CO₂, taken from IPCC (1994), increases considerably in the 21st century with possibly large consequences for the temperature in the troposphere and stratosphere. The CH₄ concentration increases in most scenarios. This may affect stratospheric ozone depletion through the formation of water vapor in the stratosphere and enhancement of the production of the reservoir compound HCl. N₂O also increases in concentration but relatively less than for CO₂ and CH₄. The CFC's, methyl chloroform and carbon tetrachloride, decreases in concentration in all future scenarios. Measurements (Montzka *et al.*, 1996; ALE/GAGE network, private communications) already show a decrease in concentration in methyl chloroform and carbon tetrachloride since a few years, while the concentration of CFC-11 has stabilized since approximately 1994. The concentration of CFC-12 still shows a small increase.

Table 1.

Yearly averaged ozone column (DU) in 1990, ozone column trend from 1980 to 1990 (% per decade) at 47°N with trends for CH₄, N₂O and temperature varying.

Simulation	Characterization scenario				Ozone ² column DU	Relative ³ to run ⁴ (%)	Ozone trend (%dec)
	CFC ₄ halon	CH ₄	N ₂ O	temp			
1 CH ₄ ,N ₂ O fixed	Tr	1900	1900		379.2	-3.0	-5.8
2 N ₂ O trend	Tr	1900	Tr		379.4	-3.0	-5.6
3 CH ₄ trend	Tr	Tr	1900		391.1	0.0	-4.4
4 CH ₄ ,N ₂ O trend ³	Tr	Tr	Tr		391.0	reference ³	-4.3
5 CH ₄ trend	1900	Tr	1900		435.5	11.4	0.1
6 N ₂ O trend	1900	1900	Tr		430.1	10.0	-0.2
7 CH ₄ ,N ₂ O trend	1900	Tr	Tr		433.3	10.8	0.0
8 Temp. fixed	Tr	Tr	Tr	1900	381.1	-2.5	-4.2
9 Temp. trend	Tr	Tr	Tr	Tr5	390.9	0.0	-3.5

- 1) Tr = trend in emissions of CFC's, CH₄ and N₂O from 1900 to 1990. For CO and NO_x a trend in surface concentrations is applied; 1900 = fixed 1900 values are used; a blank cell means that fixed 1990 values are used.
- 2) Estimated total anthropogenic change in ozone column at 47°N in 1980 is -4.5% and in 1990 -8.6% relative to 1900.
- 3) Simulation 4 is considered as a reference scenario; the others are compared with this one.
- 4) CFC stands for all CFC's, HCFC's, methyl chloroform, carbon tetrachloride, halons, methyl chloride and methyl bromide.
- 5) Dynamical feedback and heterogeneous reactions on PSC's are not taken into account.

3.1. Historical changes in ozone: CH₄ trend

Table 1 shows the ozone column in 1990 and the trend in ozone column over the period 1980 to 1990 at 47°N for various time-dependent scenario simulations from 1900 to 1990. The emission trends, based on gradual continuous changes, do not take into account observed fluctuations in the concentration of some of the compounds in the last decade. In most of the simulations summarized in Table 1 the emissions of CFC's and related chlorine and bromine compounds show a trend from 1900 to 1990; the effect of

CH₄, N₂O and temperature changes are studied in addition to this chlorine trend.

A trend in the emissions of CFC's and related compounds alone (simulation 1) gives an ozone column of 379.2 DU and a trend in ozone column of -5.8% per decade from 1980 to 1990. Applying a trend in CH₄ emissions in addition to this (simulation 3) yields a 3% thicker ozone column in 1990 and a smaller ozone trend of -4.4% per decade. That is, the trend in CH₄ emissions this century has reduced the destruction of the ozone layer from 1980 to 1990 by approximately 1.4% per decade. This positive trend comes clearly from the interaction of CH₄ with chlorine in the stratosphere. Figure 1 shows the increase in CH₄ of 80% in the whole atmosphere caused by the trend in CH₄ emissions from 1900 to 1990. The reaction $\text{CH}_4 + \text{Cl} \Rightarrow \text{HCl}$ results in an increase in HCl of approximately 18% in the lower and 24% in the middle stratosphere. (These percentages are yearly averaged values over the designated areas.) The increase in HCl means that the photostationary equilibrium of active chlorine compounds (ClO_x) shifts more to the reservoir HCl, reducing the concentrations of Cl and ClO, which are the important compounds for catalytic destruction of stratospheric ozone. Cl and ClO are reduced by approximately 20% to 25% in the whole stratosphere (Fig. 1) resulting in an increase of 2% to 4% in ozone in the lower stratosphere. In the upper stratosphere the increase reaches 6% to 8% but this area hardly contributes to the ozone column. The increase in CH₄ in this century causes an increase in H₂O of 1% in the lower, 8% in the middle and 15% in the upper stratosphere. OH, formed in the stratosphere by the reaction $\text{O}(^1\text{D}) + \text{H}_2\text{O}$, increases by approximately 7% in the lower and middle stratosphere. This causes extra ozone destruction by the catalytic HO_x cycles, but is only a small effect.

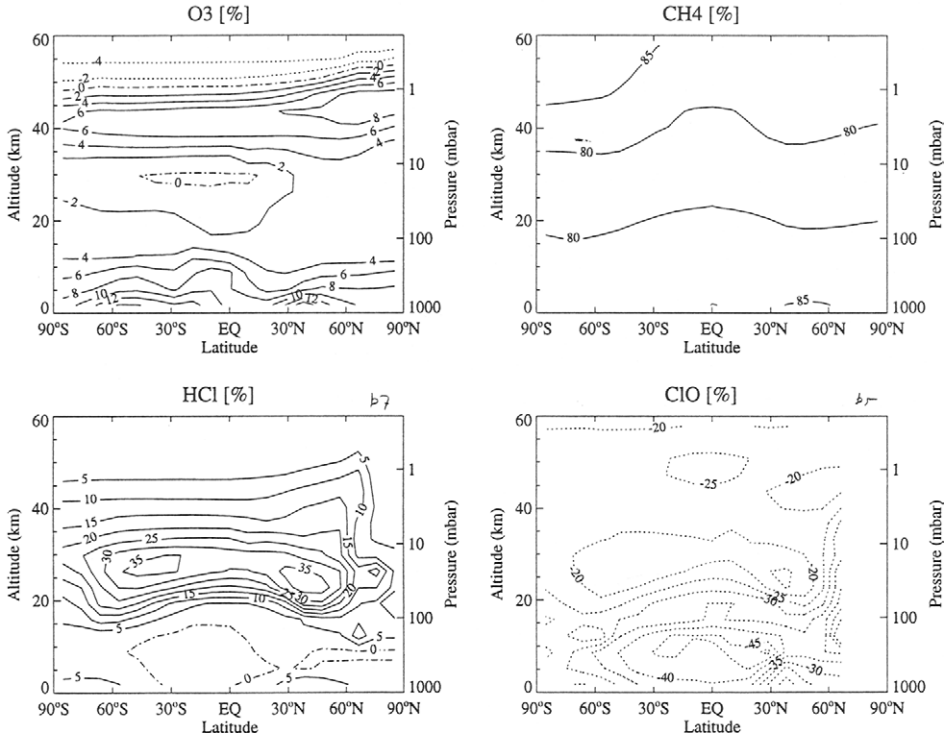
Simulation: CH₄ emissions trend

Figure 1. Relative contribution (in %) to the concentrations of O₃, CH₄, HCl and ClO in January 1990 caused by the trend in CH₄ emissions from 1900 to 1990. Fixed 1990 surface concentration of CO and NO_x and a trend in emissions from 1900 to 1990 for N₂O and all chlorine and bromine compounds. Simulation 4 minus 3 of Table 1.

The increase in CH_4 concentration hardly affects the bromine compounds since the bromine reservoir HBr is not produced by the reaction $\text{Br} + \text{CH}_4$ but by $\text{Br} + \text{HO}_2$. Furthermore, HBr is a less stable compound than HCl and therefore a less effective reservoir. The increase in CH_4 emissions in this century changed the Br concentration in the stratosphere by -4% and BrO by +0.1%.

The increase in methane emissions this century results in less ozone destruction by chlorine compounds (+1.5% per decade) and slightly more destruction by increased H_2O (-0.1% per decade). The importance of the interaction between chlorine and CH_4 for ozone is also clear from simulation 5, in which a trend in CH_4 alone and not in CFC emissions is applied. The CH_4 emission result is a small positive trend in the ozone column of 0.1% per decade, while the much lower chlorine levels in the lower stratosphere, coming only from natural CH_3Cl emissions, yield an 11% thicker ozone column in 1990.

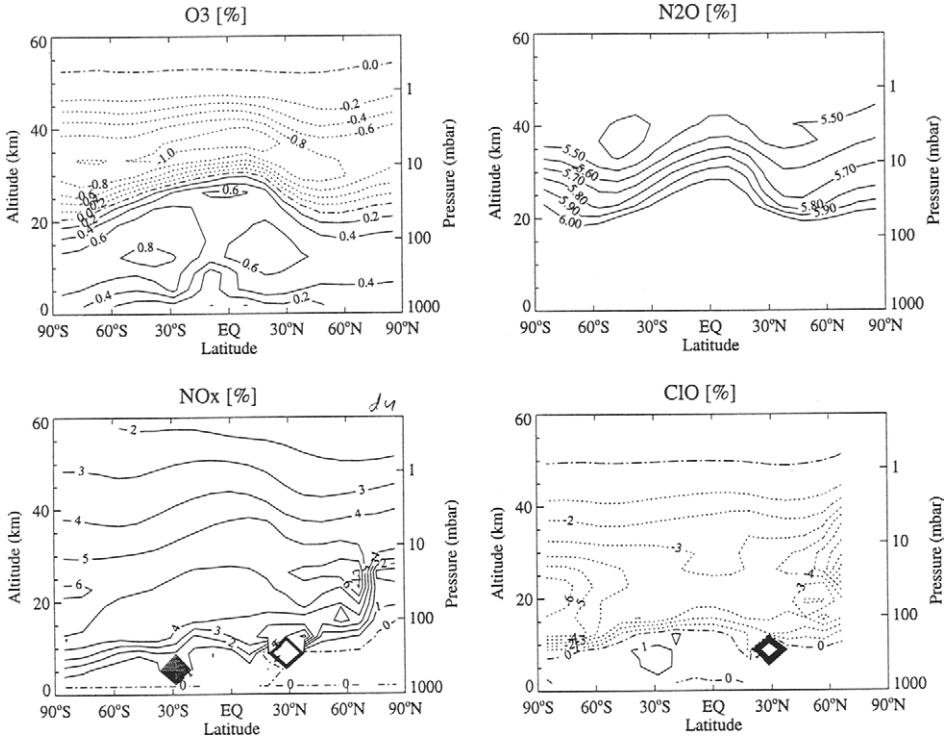
Simulation: N₂O emissions trend

Figure 2. Relative contribution (in %) to the concentrations of O₃, N₂O, NO_x and ClO in January 1990 caused by the trend in N₂O emissions from 1900 to 1990. Fixed 1990 surface concentration of CO and NO_x and a trend in emissions from 1900 to 1990 for CH₄ and all chlorine and bromine compounds. Simulation 4 minus 2 of Table 1.

3.2. Historical changes in ozone: N₂O trend

The trend in N₂O emissions from 1900 to 1990 has a small effect on the ozone column and the ozone column trend. Comparing simulations 1 and 2 or 3 and 4 shows that the N₂O trend yields a trend in ozone of +0.2% per decade or +0.1% per decade, respectively. This positive contribution of N₂O comes from the interaction of nitrogen and chlorine compounds in the stratosphere. N₂O emissions on their own cause an increase in NO_x in the stratosphere which destroys ozone catalytically. Simulation 6

shows a trend in ozone of -0.2% per decade from the trend in N_2O emissions alone (no CFC trend applied). But if CFC emissions also increase the interaction between NO_x and ClO in the stratosphere yields the chlorine reservoir $ClONO_2$, causing a shift in the photochemical equilibrium of chlorine compounds away from Cl and ClO yielding a smaller ozone destruction. This diminishing effect on ozone destruction by $ClONO_2$ formation is larger than the increasing effect by NO_x . Figure 2 shows that an increase in N_2O emissions this century results in a 6% larger N_2O concentration, an increase of NO_x of 5% and of $ClONO_2$ of 1% and a decrease of ClO of 4%, all in the lower stratosphere. There is no large interaction between CH_4 and N_2O emissions which affects ozone formation as can be seen from the simulations 4 and 7 and when comparing them with the others.

3.3. Historical changes in ozone: temperature trend

Radiative-forcing global-mean temperature changes in the atmosphere are calculated from changes in concentrations using the OGI-1D radiative convective model from MacKay and Khalil (1991). The calculated temperature change for 1990 is 0.67 K for the troposphere, which is somewhat higher than the current analyzed global mean-surface temperature increase of 0.3 to 0.6 K (IPCC, 1994). The current radiative forcing calculated with the OGI-1D model agree reasonably well with the values reported by IPCC (1994). The calculated tropospheric temperature changes in 2100 vary between 1.65 and 3.68 K relative to 1900 corresponding with 0.98 to 3.01 K relative to 1990. These values are very close to the best estimates from IPCC for the temperature change in 2100, ranging from 1 to 3.5 K relative to 1990. Larger temperature changes occur in the stratosphere. Our calculations reveal a large amount of cooling in the stratosphere from CO_2 and a slightly smaller amount from ozone. Randel and Cobb (1994) inferred a temperature trend from satellite observations. They found a decrease in temperature in the lower stratosphere ranging from -0.5 to -1.5 K from 1979 to 1990. Radio sonde measurements (WMO, 1994) of the lower stratospheric temperature show a decrease of 0.25 to 0.4 K per decade over the last three decades. These observations are in agreement with our calculations. Our calculations give a change in temperature in the lower stratosphere of approximately 0.45 K from 1980 to 1990. The future scenarios

show large decreases in stratospheric temperatures in the 21st century. Relative to 1990, the temperature changes range from -3.26 K for IS92c to -9.75 K for IS92e. The scenarios IS92a and IS92b can be considered as mid-range values, IS92e and IS92f are on the high end of the spectrum and IS92c and IS92d on the low end. Since the radiative forcing from stratospheric ozone depletion decreases in the 21st century, the stratospheric temperature decrease originates mainly from changes in CO₂ emissions.

Simulations 8 and 9 show the effect of the trend in temperature on the ozone column as calculated with a radiative model. The 3K temperature decrease in the stratosphere from 1900 to 1990 yields an increase in the ozone column of 2.5%, while the trend in the ozone column from 1980 to 1990 increases from -4.2% per decade to -3.5% per decade. The higher ozone levels with lower temperatures probably comes from the temperature dependence of the odd oxygen cycle, i.e. the Chapman cycle. Stratospheric ozone levels are, according to the Chapman cycle, proportional to the production of ozone by the reaction $O + O_2$, divided by the ozone destruction by the reaction $O + O_3$. The former reaction rate increases with decreasing temperature, while the latter decreases. So the increase in ozone production and decrease in ozone destruction with decreasing temperature yields higher ozone levels in the stratosphere. The increase in ozone is further assisted by a decrease in NO_x (-2%), OH (-3%) and ClO (-1%) in the lower stratosphere in 1990 relative to 1900, reducing catalytic destruction of ozone by these compounds. The decrease in temperature in the stratosphere comes largely from CO₂ and the effect of a temperature trend can therefore also be viewed as resulting from the increase in CO₂ emissions in this century. The temperature change from stratospheric ozone depletion is therefore estimated to be responsible for a +0.3% per decade ozone trend. It is clear that the effect of ozone destruction on the ozone trend is hard to estimate with a model that does not treat the temperature feedback interactively. The estimated +0.3% per decade contribution of ozone itself is therefore only an indication of the size of the feedback effect and will probably be smaller, since such feedbacks usually diminish the imposed changes.

3.4. Future changes in ozone: 1990-2100

The effects of a trend in emissions in CH₄, N₂O and CO₂ in future scenarios (1990 to 2100) are shown in Table 2. In simulation 10 to 17 the IS92a scenario is applied, a mid-range scenario of the IPCC (Pepper *et al.*, 1992) scenarios. In the original IS92a scenario the CFC emissions are much higher than can be expected regarding the development of these emissions in the last few years (Montzka *et al.*, 1996) and the emissions also do not agree with the latest international agreements as the Copenhagen amendments to the Montreal Protocol. For emissions of the CFC's and related compounds IPCC (Pepper *et al.*, 1992) case 6 scenario is used for all simulations mentioned in Table 2. This scenario, originally already part of the IS92d and IS92e scenarios resembles the Copenhagen amendments. In the IS92a scenario the emissions, and consequently concentration, of CH₄, N₂O and CO₂ increase continuously. Since after 2000 the ozone layer is expected to start to recover, which will increase stratospheric temperatures, and CO₂ concentration is projected to increase according to the IS92 scenarios, the decrease in temperature in the stratosphere can be attributed to CO₂. Measurements of the ozone column do not show a depletion before the end of the 1970's. We will therefore use the ozone column in 1980 as a measure of the recovery of the ozone layer in the 21st century (WMO, 1994). The calculated total anthropogenic change in the ozone column since 1900 was -8.6% in 1990. The column of Table 2 named 'Recovery ozone layer' gives the year in which the ozone column reaches 1980 levels. Until approximately the year 2000 the thickness of the ozone layer will continue to decline because of the high chlorine levels in the atmosphere (Montzka *et al.*, 1996; WMO, 1994).

Table 2. Change in yearly average ozone column (%) at 47°N

Simulation	Characterization scenario:				Relative to 1990 (%) ¹			Recovery ozone layer
	CFC ₃ halon	CH ₄	N ₂ O	temp	2020	2050	2100 ²	
<u>IS92a³: temp. fixed</u>								
10 CH ₄ ,N ₂ O fixed	Tr	1990	1990	1990	-1.9	1.9	5.4	2080
11 N ₂ O trend	Tr	1990	Tr	1990	-1.9	1.7	4.6	2095
12 CH ₄ trend	Tr	Tr	1990	1990	-1.1	3.4	6.9	2060
13 CH ₄ ,N ₂ O trend	Tr	Tr	Tr	1990	-1.1	3.2	6.1	2065
<u>IS92a³: Temp.trend</u>								
14 CH ₄ ,N ₂ O fixed	Tr	1990	1990	Tr	-0.4	5.4	12.5	2045
15 N ₂ O trend	Tr	1990	Tr	Tr	-0.4	5.2	11.7	2045
16 CH ₄ trend	Tr	Tr	1990	Tr	0.4	7.0	14.2	2040
17 CH ₄ , N ₂ O trend	Tr	Tr	Tr	Tr	0.4	6.8	13.4	2040

- 1) Yearly average ozone column in 1990 is 391.0 DU (simulation number 4 in Table 1)
- 2) Estimated total anthropogenic change in ozone column at 47°N in 1980 is -4.5% and in 1990 is -8.6% relative to 1990.
- 3) For the CFC's and related compounds not the original scenario is used but IPCC (Pepper *et al.*, 1992) case 6 scenario, which resembles the Copenhagen amendments to the Montreal Protocol.
- 4) The change in temperature is caused mainly by increases in CO₂ emissions. Dynamical feedback and heterogeneous reactions on PSC's are not taken into account.

According to our calculations (Table 2) the ozone column at mid-latitude will be 1.9% below 1990 levels in 2020 (simulation 10). From approximately 2040 onwards, ozone will reach 1990 levels (see also Velders, 1995b). This is with fixed 1990 emissions for CH₄ and N₂O. In approximately 2080 the ozone column will reach 1980 levels and in 2100 the ozone column will be 5.4% thicker than in 1990. An increase in N₂O emissions

in addition to this causes the ozone layer thickness to increase less because of an increase of NO_x in the stratosphere. The lower chlorine levels in the next century reduce the interaction between the NO_x and ClO_x compounds to form the reservoir ClONO_2 . As shown before, an increase in CH_4 emissions reduces the ozone destruction by ClO_x . The CH_4 increase causes a 1.5% thicker ozone layer in 2100 (comparing simulations 10 and 12). The recovery of the ozone layer will be reduced by 20 years from 2080 to 2060. The stronger interaction between CH_4 and chlorine, compared with NO_x and chlorine, is responsible for the continuous positive influence (thicker ozone layer) with increasing CH_4 emissions. According to simulation 10 the ozone levels are expected to drop below 1980 levels in 2080, which is later than the year 2045 reported by Daniel *et al.* (1995) and WMO (1994). The difference is most likely caused by differences in the emission data in the phase-out period (1990-2010) of CFC's and related compounds, since the Montreal protocol and its amendments are based on production limitations and not on emissions.

A decrease in temperature in the stratosphere of 7 K in 2100 relative to 1990, corresponding with scenario IS92a, has a large impact on the ozone layer in the next century. Comparing simulations 14 to 17 with 10 to 13, the effect of the temperature decrease since 1990 is more than a doubling of the ozone column change in 2100. The inclusion of the temperature trend in the simulations causes a faster recovery of the ozone layer: from approximately 6% to 12% in 2100 relative to 1990. The increase in ozone column thickness in 2100 with the incorporation of the temperature trend yield is larger than the total calculated anthropogenic change in ozone column (-8.6% in 1990). As mentioned before, the effects of temperature changes are difficult to model because of the nature of interactions between ozone and temperature itself. It can best be done using a model which calculates the temperature and ozone changes interactively instead of off-line with a separate model, as has been used here. The changes in ozone originating from temperature (CO_2) changes will be diminished with an interactive model. Large temperature decreases in the stratosphere might also cause extra formation of polar stratospheric clouds (PSC's) in winter in polar areas and possibly also at mid-latitudes and in other seasons. This might cause a large depletion of stratospheric ozone through heterogeneous reactions on the surfaces of the PSC's. If this will happen is

speculative, and if so it will probably only occur in winter at high latitudes and in the first half of the next century, when chlorine levels are still high. With a temperature trend in addition to a CH₄ emission trend the ozone column could reach 1990 levels just before 2020 and approximate 1980 values in 2040. The increase in CO₂ emissions, almost completely responsible for the temperature trend in the stratosphere after 2050, causes the ozone layer to reach pre-industrial levels by approximately 2070. A trend in N₂O emissions slows this recovery while a CH₄ trend accelerates it.

4. CONCLUSIONS

Emissions of greenhouse gases affect stratospheric ozone depletion

CFC's and other chlorine- and bromine-containing compounds are responsible for the main destruction of stratospheric ozone; however greenhouse gas emissions can affect the ozone column as well:

Table 3. Contributions to the trend in ozone column from 1980 to 1990 at 47°N and the recovery of the ozone layer as indicated by the year when 1980 ozone levels are reached

Compounds emitted	Ozone column trend (% per decade)	Ozone recovery 1980 levels ²	Mechanism	Remarks
CFCs, HCFCs, CCl ₄ , CH ₃ CCl ₃ , Halons, CH ₃ Br	-5.8	2080		
N ₂ O	+0.1 ¹	+15 ¹	NO _x , Formation of reservoir	
CH ₄	+1.4	-20	Formation of reservoir	
CO ₂	+0.4	-25	Temperature	Feedback and PSC's ignored
CH ₄ + N ₂ O	+1.5	-15		
CH ₄ + N ₂ O + CO ₂	+2.0	-40		

- 1) Contribution of the emissions of the compounds on top of the CFC, HCFC, CCl₄, CH₃CCl₃, halon and CH₃Br contribution (row 1).
- 2) Ozone layer recovered: the year the ozone layer reaches a level corresponding to the ozone layer in 1980.
- 3) n.a. = 'not assessed'.
- 4) Only the effect of the injection of aerosols from volcanic eruptions is calculated, not that of tropospheric aerosols.

Greenhouse gas interactions improve agreement with measurements

Taking into account the effects of a trend in CFCs, CH₄, N₂O and CO₂ emissions results in a good agreement between the calculated (-3.8% per decade) and measured (-4.0% per decade from TOMS and Dobson measurements; WMO, 1994) trend in ozone column at

mid-latitude in the Northern Hemisphere from 1980 to 1990.

CH₄ emissions accelerate the recovery of the ozone layer

The interactions between greenhouse gases and stratospheric ozone also have an effect on the recovery of the ozone layer in the 21st century. The international measures (*i.e.* Montreal) are likely to reduce the chlorine levels in the stratosphere in the coming decades. The reduction in emissions of CFC and related compounds alone will result in 2050 in an ozone column 1.9% thicker than in 1990. Anticipating a business-as-usual scenario (IS92a) for N₂O and CH₄ in addition to the chlorine reduction yields 0.2% smaller and 1.5% larger increases, respectively. With fixed CH₄, N₂O and CO₂ emissions an ozone column corresponding with 1980 can be reached in approximately 2080. A methane trend as in scenario IS92a reduces this to approximately 2060, while an additional CO₂ trend (temperature decrease) reduces it to approximately 2040.

CO₂ increases can initially increase the ozone column

The CO₂ emission is largely responsible for a large decrease in temperature in the stratosphere in the 21st century: -7 K in 2100 relative to 1990. This results in an extra increase in ozone column of approximately 3.5% in 2050 relative to 1990. The temperature effect can be diminished if dynamical interactions in the atmosphere are taken into account interactively in a model. The decrease in temperature in the stratosphere might increase the occurrence of PSC's in winter, in polar regions but possibly also at mid-latitudes and in other seasons. If this happens a strong decrease in stratospheric ozone might occur from the temperature decrease. This effect is not considered here. A temperature decrease in the stratosphere, from an increase in CO₂ emissions will therefore, at least initially, yield a thicker ozone layer, as shown above.

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