Stratospheric Ozone and Temperature Changes in the Past: The Impact of Increased Concentrations of CFCs in Simulations with a Chemistry-Climate Model

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Introduction

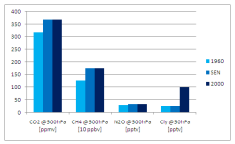
In the last decades of the 20th century a decrease in the stratospheric ozone abundance has been observed especially in the southern polar region but also at tropical and mid-latitudinal stations (e.g. WMO, 2002). Furthermore, the increase of atmospheric greenhouse gases (GHGs) leads to a temperature increase in the troposphere but to a cooling of the stratosphere (e.g. WMO, 2002).
These changes in ozone and temperature between 1960 and the end of the 20th century are investigated by analysing simulations with the Chemistry-Climate-Model (CCM) EMAC. In order to analyse the impact of increasing emissions of ozone depleting substances (ODSs) (e.g. chlorofluorocarbons, CFCs) from 1960 to 2000 different sensitivity studies have been performed: two reference simulations with boundary conditions for the year 1960 and 2000, respectively, and one simulation with CFC emissions fixed at 1960 but GHG concentrations for 2000. These simulations allow to isolate the ozone and temperature changes that are caused by the CFC increase only and separate the CFC effect from other processes affecting ozone, e.g. climate change.

Model Setup & Experimental Design

- Chemistry-Climate Model (CCM) ECHAM/MESSy (**EMAC**) version 1.7 (Jöckel et al., 2006): Three-dimensional atmospheric circulation model (ECHAM5) with **fully coupled interactive chemistry (MECCA)** (Sander et al., 2005)
- **EMAC-FUB Configuration:**
  - FUBRad shortwave radiation scheme (Nissen et al., 2007)
  - Spectral T42 resolution (2.8°x2.8°) and 39 layers in the vertical with a model top at 0.01 hPa (~80 km)
- Prescribed sea surface temperatures (SSTs) and sea ice concentrations (SICs)

Definition of sensitivity studies :
- "**Timeslice**" experiments over 20 years (model run with fixed boundary conditions)
- Present day ('**2000**') and past ('**1960**') reference simulations
- Sensitivity study with greenhouse gas (GHG) concentrations for 2000 and CFCs fixed at 1960 level ('**SEN**')

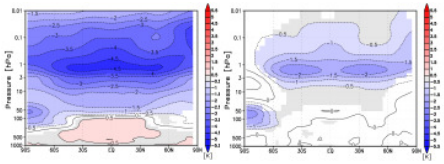
Name		GHGs	CFCs	SSTs/SICs
1960	timeslice	Observations for the year 1960	Observations for the year 1960	modelled (MPI-OM) 1955-1964 average
2000	timeslice	Observations for the year 2000	Observations for the year 2000	modelled (MPI-OM) 1995-2004 average
SEN	timeslice	Observations for the year 2000	Observations for the year 1960	modelled (MPI-OM) 1995-2004 average



Annual mean global mean mixing ratios of the important anthropogenic GHG substances (CO_2, CH_4 and N_2O) at 500hPa and of inorganic chlorine (Cl_y) at 50hPa originating from CFCs for the 3 model experiments.

Differences between these experiments:
1) '2000'-'1960': GHGs and CFCs change
2) '2000'-'SEN': CFCs change at high level of GHGs
3) 'SEN'-'1960': GHGs change at low level of CFCs

Temperature



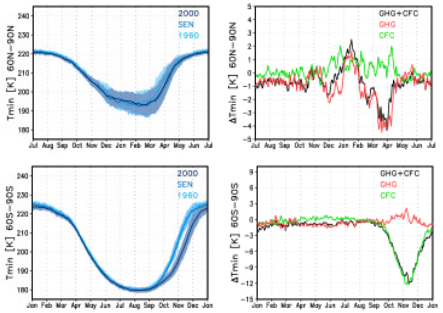
Annual mean temperature change in K between 1960 and 2000 (left) and temperature change due to CFC increase only (right). Statistically significant changes are coloured (95% confidence level).

- Up to **50%** of the temperature decrease in the upper stratosphere caused by the increasing chlorine abundance and the following O_3 loss
- Cooling of the SH polar lower stratosphere mainly (**70-100%**) caused by the O_3 loss due to CFC increase.

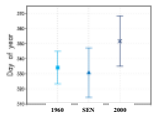
→ Cooling in the upper troposphere (200-100hPa) stronger without climate change

- **NH**:
Decrease in the minimum temperature in early spring between 1960 and 2000 not caused by increasing CFCs or related processes

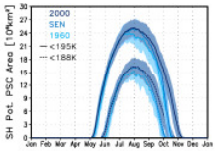
- **SH**:
- Lower minimum values (~1K) from January to September for the year 2000 simulation caused by GHG increase
- Large difference in spring (up to 12K) explained by the CFC increase: delayed springtime warming because of lower O_3 concentrations
- Delayed temperature increase reflected in a longer PSC-period and larger O_3 loss
- Delayed transition from winter to summer circulation: winter conditions >15 days longer



Annual cycle of the minimum temperature (left) and the differences between the experiments (right, see green box in ‚Experimental Design') in the northern (top) and southern (bottom) polar stratosphere (50hPa) in K. Shading denotes 1σ.

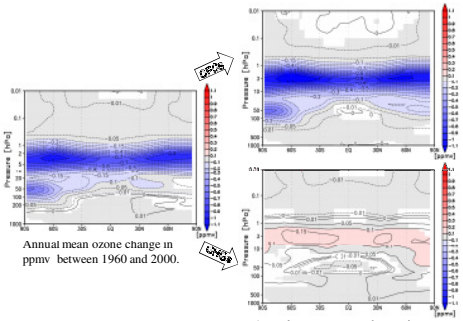


Day of the year when the zonal mean zonal wind (65S, 50hPa) falls below 10m/s. Error bars denote 1σ.



Annual cycle of the potential area for PSC type I (T < 195K) and II (T < 188K) formation in the southern polar stratosphere (50hPa) in million km². Shading denotes 1σ.

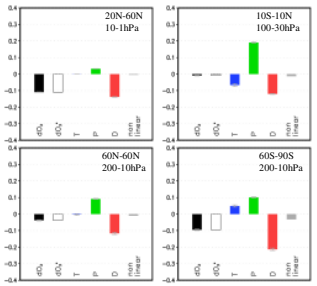
Ozone



Annual mean ozone change in ppmv between 1960 and 2000.

Annual mean ozone change in ppmv between 1960 and 2000 due to CFC increase (top) and GHG increase (bottom).

- Global stratospheric ozone decrease between 1960 and 2000
- Maximal absolute change in the upper stratosphere and SH polar lower stratosphere
- O_3 loss mainly due to the chlorine increase
- O_3 loss larger without climate change (up to 40% in the tropical upper stratosphere; up to 60% in the SH polar lower stratosphere)
- Reduced O_3 loss due to GHG induced cooling in the stratosphere
- Weak signal of O_3 decrease in the tropical lower stratosphere due to GHG increase

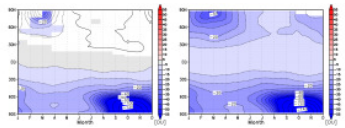


Contribution of chemical production P, destruction D and transport T to the relative ozone change dO3 in different altitudes and latitude ranges due to CFC increase only. dO3* is for the validation of the separation. Method adapted by Garny et al., 2011.

- **Contribution of chemistry and transport to relative ozone changes due to CFCs only:**

- **20N-60N, 10-1hPa**: O_3 change due to a modified chemistry (destruction rate)
- **20S-20N, 100-30hPa**: Changes in transport, production and loss in balance: no relative O_3 change
- **60N-90N, 200-10hPa**: O_3 change due to modified destruction rates reduced by a positive O_3 change due to production
- **60S-90S, 200-10hPa:** Large O_3 decrease due to a intensified heterogeneous chlorine chemistry, but weakened by changes in transport and production leading to an increase in O_3

- **Total Ozone**: SH change dominated by CFC increase; NH change modified by climate change



Annual cycle of Total Ozone change in DU between 1960 and 2000 due to CFC and GHG (left) and due to CFC only (right). Statistically significant changes are coloured (95% confidence level).

Summary

Temperature
The impact of increasing chlorine concentrations on stratospheric ozone and temperatures betweeen 1960 and 2000 is analysed in sensitivity studies with the Chemistry-Climate Model EMAC.
The temperature decrease by up to 4.5K in the upper stratosphere can be attributed by nearly 50% to the ozone loss caused by increased chlorine abundances. In the southern polar lower stratosphere, however, the temperature decrease is mainly caused by ozone loss, only slightly modified by GHG induced processes. The increasing CFC concentrations do not result in lower minimum temperatures in the polar regions, but lead to a delayed springtime temperature increase and delayed circulation transition in the southern hemisphere. While the maximum PSC area in the southern polar region is not affected by CFC-related cooling, the period when PSC formation is possible is significantly longer.

Ozone
The ozone loss in the stratosphere is directly related to the increase of chlorine in the atmosphere. However, the CFC increase alone leads to lower ozone mixing ratios than caused by both GHG and CFC increased. By analysing the contributions of chemistry and transport to the relative ozone change it can be shown that the effect of increasing CFCs depends on altitude and latitude and that a modification of the ozone transport plays also an important role.
The change in the O_3 column due to the chlorine increase is dominant in the southern hemisphere throughout the year. In the northern hemisphere, however, only the springtime ozone loss can be attributed to CFC increase. The decrease in column ozone due to CFC in the other seasons is balanced by ozone changes related to climate change.

Acknowledgements

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