Effect of future increase in nitrous oxide on stratospheric ozone

S. Meul, S. Oberländer-Hayn, U. Langematz

Freie Universität Berlin, Berlin, Germany

Introduction

With the successful regulation of halogen containing ozone depleting substances (ODS) in the Montreal Protocol and its amendments, today nitrous oxide (N_2O) is the most important ozone depleting species emitted by anthropogenic activity (e.g., Portmann et al., 2012). The future increase of carbon dioxide (CO_2) and methane (CH_4), however, will have a mitigating effect on the ozone depleting potential of N_2O (e.g., Stolarski et al., 2015; see also box on the right). Thus, the future ozone depletion due to N_2O strongly depends on the emission scenarios of CO_2 and CH_4.

In our study we quantify the contribution from N_2O to ozone loss and thus, the future potential of N_2O to harm the stratospheric ozone layer under the extreme RCP8.5 scenario at the end of the 21st century when the stratospheric halogen loading will have returned to pre-1980 levels. Based on the analysis of multi-year simulations with the chemistry-climate model EMAC we examine the impact of increasing N_2O on ozone and the feedbacks with greenhouse gas (GHG) induced temperature and circulation changes as well as CH_4 induced changes in stratospheric chemistry.

Sources and sinks of NO_y in the stratosphere:

Source:
- $N_2O + O^1D \rightarrow 2\,NO$

Sink:
- $N + NO \rightarrow N_2 + O$
- transport to the troposphere

N + NO reaction rate increases with lower temperature because the concentration of N atoms is increased ($N+O_2 \rightarrow NO+O$ reaction rate decreased with cooling)

Model & Experiments

- Chemistry-climate model EMAC v2.50.7 (ECHAM/MESSy Atmospheric chemistry; Jöckel et al., 2015, GMDD)
- T42L47 resolution (up to 0.01 hPa)
- Time slice simulations for the years 2000 and 2100
- Integration over 40 years (+5 years spin-up)
- Boundary conditions (overview in Table 1):
  - Future GHG levels: RCP8.5 scenario (Meinshausen et al., 2011)
  - Future ODS concentrations: A1 scenario (WMO, 2007)
  - Prescribed fields for sea surface temperature (SST) and sea ice concentration (SIC) from simulations with the MPI-ESM (Schmidt et al., 2013)
  - Nudged QBO, no solar variability

\+ two transient simulations (1960-2100, EMAC v1.10): RCP6.0 and RCP8.5

Simulation	CO2	CH4	N2O	ODS	Trop. precursor	SST/ SIC
REF2000	2000	2000	2000	2000	2000	1995-2004
REF2100	2100	2100	2100	2100	2100	2095-2104
N2O_2100	2000	2000	2100	2100	2000	1995-2004
CH4_2100	2000	2100	2000	2100	2000	1995-2004
GHG_2100	2100	2100	2100	2000	2000	2095-2104
ODS_2100	2000	2000	2000	2100	2000	1995-2004

Table 1 Overview and boundary conditions of the simulations.

Future NO_y changes

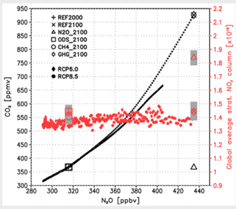

Fig. 1 N_2O and CO_2 boundary conditions for the timeslice and transient simulations (black symbols) and the relation between surface N_2O and stratospheric NO_y column in 10^{16} molecules/cm² (red symbols, y-axis on the right; gray shading indicates $\pm1\sigma$).

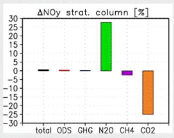

Fig. 2 Change in the stratospheric NO_y column between 2000 and 2100 and the contribution from ODSs and GHGs. The GHG effect is separated into the contribution from N_2O, CH_4 and CO_2.

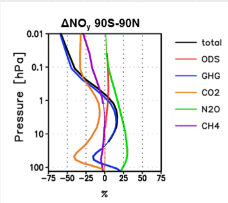

Fig. 3 Global mean annual mean relative differences in NO_y mixing ratio between 2000 and 2100 and the contributions from ODS, GHG, CO_2, CH_4 and N_2O.

- The future increase of N_2O emissions affects the amount of inorganic nitrogen (NO_y= NO+NO_2+reservoir species) in the stratosphere (Fig. 1, 2, 3).
- The NO_y increase caused by a certain N_2O increase depends on the concentration of the GHGs CO_2 and CH_4 (Fig. 2, 3)
- 37% higher N_2O levels lead to an increase of stratospheric NO_y by 28% if the CO_2 and CH_4 are not changed (= year 2000 level; Fig. 1 and 2) .
- Accounting for the increase of CO_2 and CH_4 that is projected for the RCP8.5 scenario, the increase of stratospheric NO_y is reduced to less than 1%.
- The largest impact on the NO_y change is found for CO_2, while CH_4 mainly affects NO_y in the mesosphere.

Future ozone changes

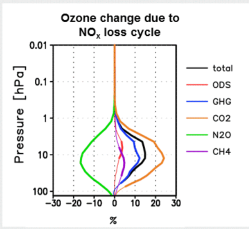

Fig. 4 Global mean annual mean relative differences in ozone mixing ratio due to changes of the loss rate in the catalytic NO_x-cycle between 2000 and 2100 and the contributions from ODS, GHG, CO_2, CH_4 and N_2O.

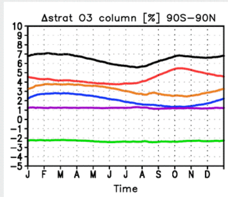

Fig. 5 Annual cycle of global mean relative differences in the stratospheric ozone column between 2000 and 2100 and the contributions from ODS, GHG, CO_2, CH_4 and N_2O.

- The increase of N_2O emissions and the concomitant increase in stratospheric NO_y (under year 2000 conditions for CO_2 and CH_4) leads to a larger loss rate in the catalytic NO_x-cycle and an ozone decrease by up to 18% (Fig. 4).
- The stratospheric ozone column is reduced by 2% throughout the year (Fig. 5).
- No other species emitted by anthropogenic activity (considered in this study) causes an ozone decrease at the end of the 21st century.
- Largest strat. ozone column increase due to ODSs (4-6%) and CO_2 (3-4%).

Sensitivity of NO_y changes to CO_2

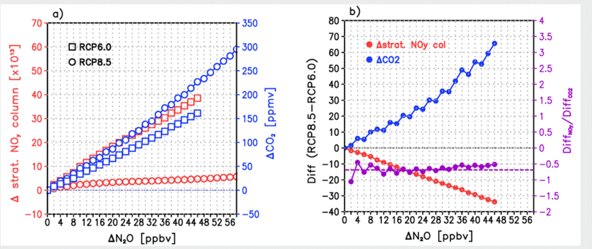

Fig. 6 a) Change of stratospheric NO_y column in 10^{13} molecules/cm² (red) and CO_2 mixing ratio in ppmv (blue; right y-axis) for a given N_2O increase (bins of 2 ppbv, starting in the year 2040) in the transient simulations RCP6.0 (square) and RCP8.5 (circle).
b) Differences between the RCP6.0 and RCP8.5 runs in the NO_y column (red) and CO_2 (blue) change per N_2O increase. The purple line shows the quotient between the red and the blue line (y-axis on the right). The purple dashed line represents the quotient but derived from the timeslice simulations.

- To analyse the effect of different CO_2 levels on stratospheric NO_y with identical N_2O changes, we use the transient simulations RCP6.0 and RCP8.5.
- By binning the changes in NO_y and CO_2 in both simulations to equal changes in N_2O, the sensitivity of NO_y increase to CO_2 changes is analysed (Fig. 6a).
- The difference between the RCP6.0 and RCP8.5 runs (Fig. 6b) shows that the larger the difference between CO_2 the larger the difference in the stratospheric NO_y column: A N_2O increase of 40 ppbv causes a 7 times larger increase in stratospheric NO_y if the CO_2 increase is 30% smaller.
- The relationship between CO_2 and NO_y differences is not constant (from ~-1 to -0.5) indicating a nonlinear behaviour or the possible influence of other drivers (e.g., differences in the chlorine loading).

Estimation of stratospheric NO_y changes depending on N_2O and CO_2 changes

- Assuming linear relation between CO_2, temperature and NO_y changes:

$$\Delta NOy = \Delta N2O[ppbv] \cdot S_{N2O} + \Delta CO2[ppmv] \cdot S_{CO2}$$

  with S_{N2O} and S_{CO2} representing sensitivity parameters for the changes.

- S_{N2O} is derived from the timeslice simulations for N_2O increase only (see Fig. 1):

$$S_{N2O} = \frac{\Delta NOy}{\Delta N2O} = \frac{0.399\cdot 10^{16}}{119}\frac{molec/cm^2}{ppbv} = 3.35 \cdot 10^{13}\frac{molec/cm^2}{ppbv}$$

- S_{CO2} represents the quotient in Fig. 6 and is found to be

$$S_{CO2} = \frac{Diff_{NOy}}{Diff_{CO2}} = -0.707 \cdot\ 10^{13}\,\frac{molec/cm^2}{ppmv}$$

in the timeslice simulations.

Conclusions

In this study we have analysed the effect of increasing N_2O emissions on stratospheric NO_y and ozone in simulations with the CCM EMAC. As shown in previous studies the NO_y change resulting from increased N_2O strongly depends on the level of GHGs, in particular CO_2. We find that NO_y is increased by 28% which leads to an ozone reduction by up to 18% due to an enhanced catalytic NO_x cycle in the middle stratosphere if N_2O emissions rise following the RCP8.5 scenario for the year 2100 but CO_2 and CH_4 levels are fixed at the year 2000. The corresponding decrease of stratospheric column ozone is 2%. Accounting for increasing CO_2 and CH_4 the NO_y increase is considerably reduced due to stratospheric cooling and a more effective NO_y loss. All in all, the N_2O induced stratospheric ozone loss is overcompensated by the effect of the other GHGs.

The sensitivity of NO_y to CO_2 changes is estimated based on the timeslice simulations and tested with the help of transient simulations under the RCP6.0 and RCP8.5 scenarios. We introduce a sensitivity parameter for the effect of CO_2 changes on NO_y, which is constant when derived from the timeslice simulations (by definition) and has a slight slope when derived from the transient simulations. This indicates either nonlinearities or the impact of other processes affecting stratospheric NO_y. However, this provides a rough estimation of the stratospheric NO_y change for potential N_2O and CO_2 changes: For a N_2O increase as projected in the RCP8.5 scenario but a smaller CO_2 increase (as in RCP6.0) the resulting increase of stratospheric NO_y is more than 60 times larger compared to the increase with the RCP8.5 CO_2 increase.

References & Acknowledgments

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This work has been funded by the DFG within the Research Unit SHARP-OCF. We would like to thank the North-German Supercomputing Alliance (HLRN) and the ECMWF computing center in Reading for computing time and support.