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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Attribution of stratospheric ozone trends to chemistry and transport: a modelling study" *by* G. Kiesewetter et al.

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We thank Neil Harris for his comments on our manuscript. Referee comments are quoted in *italicized* font.

We have revised the manuscript, trying to include as far as possible the suggestions by five referees. The most important changes in our manuscript are:

- We have conducted a rerun of the model runs analyzed in the study. In this rerun,

the temperature dependence of our linearized ozone chemistry scheme (Linoz) is switched on in the upper stratosphere as well. As a consequence, former Fig. 8 has been dropped.

- We have added a model run in which the empirical polar ozone depletion rate is scaled with $EESC^2$, in order to include an upper estimate for the influence of polar chemistry on mid-latitude column ozone trends. In the runs analyzed in the original manuscript, the polar ozone depletion rate was scaled linearly with EESC.

- The trend analysis methodology has been changed. We now apply the method of connected piecewise linear trends described by Reinsel et al. (2002). This eliminates difficulties due to the misalignment of trends at the intersection of the two trend analysis periods, 1979–1999 and 2000–2009.

- The whole modelled TO3 dataset is analysed in one piece now, including overlaps between ERA-40 and ERA-Interim driven periods. While accounting for an offset between the different meteorological reanalysis periods, equal trends are used for regressing the overlap period, thus increasing the robustness of the analysis.

- A regression analysis of TO3 differences between model and observations is used to remove solar cycle and aerosol signals from the observational time series. This has resulted in a new section (now Sect. 4) and an additional figure (now Fig. 6). The modified observational time series, which is better comparable to modelled ozone, is then used in the trend analysis.

- We have included an explicit analysis of changes in column ozone trends. This has resulted in a new figure (now Fig. 9).

- The analysis of profile trends has been extended to the period 2000-2009.

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- We have tried to make the specific findings of this study clearer. In particular, the abstract has been altered, and the conclusions have been completely rewritten. Although our major conclusions do not change, new points have been added that emerge from the revised regression analysis (e.g. discussion of the significance of trend changes).

Replies to comments by Dr. Harris:

General comments.

1. there probably are good results in here, but from a single read I am not sure what they are; 2. more effort needs to be made to bring them out while some of the more mundane results are emphasised less;

We have tried to elaborate the results of our study more clearly. Although the methodology has been revised, our conclusions have not changed significantly, but have rather been expanded. The main points of our study are: 1) the methodology (CTM sensitivity runs with different components switched between EESC-dependent and constant) provides a valid and valuable approach for distinguishing contributions to TO3 trends, 2) modelled trends are in good agreement to observations and thus the trend attribution can be expected to be reasonable, 3) we undertake a quantification of the different contributing factors to TO3 trends for all latitudes in the periods 1979–1999 and 2000–2009, 4) we quantify the significance of TO3 trend changes between rising and falling EESC period, in particular the influence of meteorology. As detailed in the manuscript, the observed change in TO3 trends is partly due to changes in meteorology.

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3. the treatment of the high altitude ozone seems dismissive;

This point has been raised by Referees 2 and 3 as well, and we have undertaken a rerun of our CTM runs in which the temperature sensitivity of the Linoz scheme is switched on for all but the two uppermost model levels. On these, high temperature dependence in connection with unrealistic temperature fields leads to unrealistic ozone fields or even model crashes at single days. Agreement of modelled profile ozone trends with observed trends decreases slightly when the temperature dependence is switched on, pointing to possible issues with temperature fields (or Linoz coefficients) in the upper stratosphere. In the 2000–2009 decade, agreement between modelled and observed ozone trends is lacking in the upper stratosphere. However, column ozone trends are only marginally influenced by upper stratospheric ozone trends, and thus our conclusions concerning the attribution of observed TO3 trends are not affected significantly by the upper stratosphere.

4. the statistical analysis should be improved – in particular the two time periods should be linked;

We have followed Dr. Harris' suggestion and applied the method of piecewise linear trends described by Reinsel et al. (2002). The whole time series is analysed in one piece now, including overlaps between ERA-40 and ERA-Interim datasets. During their overlap, both time series are forced to a common trend, while an absolute offset is allowed. A change in trend is accounted for, starting in 2000, in line with the beginning decrease of ODS concentrations affecting gas phase chemistry in our CTM. In order to improve clarity, the regression methodology is detailed in Section 5.1 now.

5. the implications of using the linearised ozone scheme are not well described – the

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reference to the earlier paper is insufficient – and the authors do not convince me that it is a good enough description of the chemistry for an attribution study of long-term trends, especially when the upper stratosphere is then dealt with somewhat arbitrarily and aerosols are ignored.

The Linoz coefficients were provided to us by Juno Hsu and Michael Prather, University of California at Irvine. Linoz tables are generated from calculations with a full photochemical box model, in which stratospheric trace gas concentrations are scaled to tropospheric concentrations of long-lived source gases (N_2O, CH_4, and halocarbons). In our study, Linoz tables are generated for tropospheric source gas concentrations corresponding to years 1975, 1997 and 2007, and used for the stratospheric years 1978, 2000, and 2010. Tables are interpolated linearly between 1 Jan of these years, implying an assumed linear evolution of source gases with time. Since EESC, the key driver of ozone changes analysed in this study, showed a close to linear increase during 1980s until mid-1990s, peaked in late 1990s (the exact timing depends on the stratospheric region under consideration), and then decreased almost linearly from then, the assumption of piecewise linear evolution of source gases underlying our chemistry scheme seems justified.

Since temperature dependence is switched on in all model runs now, the upper stratosphere is no longer dealt with arbitrarily. Although agreement between modelled and observed profile ozone trends decreases sligthly in the upper stratosphere, TO3 trends remain largely unchanged.

Heterogeneous chemistry on aerosols is included in the Linoz tables, but aerosols are kept at background levels at all times. We believe that “ignoring aerosols” is indeed an advantage in this study as all ozone changes must originate in changing chemistry or meteorology, while the usual ambiguity of attributing TO3 changes in the (late) 1990s to Pinatubo aerosol (or its decrease) or changing EESC is avoided. For better comparability of modelled TO3 with observations, we now generate an observational TO3 time series with solar and aerosol signals removed by regressing

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ΔTO3 $= observations - model$ against solar flux and the aerosol optical depth. This is done in Sect. 4. Furthermore, we have detailed the section describing the Linoz chemistry scheme (Sect. 2.2) to include more information on how the tables are generated.

Specific comments.

A. Polar ozone loss is close to linear with Cly. Given this, the authors' assumption of linearity dependence ozone loss on Cly is reasonable and they should say more about the pre-1980 losses and their influence on trends, including whether they believe they were that large.

In the ACPD manuscript, we considered only a version of the polar chemistry scheme in which the polar ozone loss rate $r = 1/\tau$ (τ... ozone lifetime) was scaled linearly with EESC. While this is a reasonable assumption, as Dr. Harris states, also higher dependencies up to $r \propto \text{EESC}^2$ are reasonable (Searle et al., 1998; Hsu and Prather, 2009). In the tt model run, in which $r \propto$ EESC, the proportionality of springtime TO3 losses to EESC is less than 1, and strong polar ozone depletion is already present at the beginning of the 1980s. We have added a model run in which $r \propto \text{EESC}^2$. Also in this run, substantial ozone loss occurs around 1980, as springtime TO3 losses scale almost directly proportional to EESC. However, while the polar chemistry scheme works fine in generating reasonable trends, an exact quantification of TO3 losses for the early years is beyond the possibilities of this simple polar chemistry scheme. Besides the strong dependence on the EESC scaling, large differences in absolute numbers of TO3 losses are encountered for the different meteorological datasets. Calculations with the CTM run in full chemistry mode including a detailed polar chemistry should be undertaken in order to arrive at a reliable quantification of pre-1980 losses. Thus, while pre-1980 TO3 losses are certainly an important issue,

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we have to postpone a deeper investigation to a possible follow-up study.

B. I find the use of acronyms excessive. GSG may become useful if the community start using it, but some of the others make it hard to follow what has been done.

We have tried to reduce the number of acronyms and abbreviations as far as possible, e.g. by eliminating "E4" for ERA-40 and "EI" for ERA-Interim. Concerning model runs, the use of two-letter codes for denoting the model runs analysed here was the only rational solution we could think of, as in this case the name contains the complete information about the conditions used in this run, i.e. polar chemistry mode and gas phase chemistry mode.

References

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