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Interactive Comment

# *Interactive comment on* "The origin of ozone" *by* V. Grewe

**V. Grewe**

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Comment to Referees' comments on upper boundary

Summary of referee comments on upper boundary

Both reviewers raised the question of the impact of the model's upper boundary. One can summarize the referees concerns following referee 1: The mean state is masked by the boundary conditions.

Overview on Authors response

In general both referees are of course right that the model ECHAM4.L39(DLR)/CHEM (E39/C) does not include the Brewer-Dobson Circulation (BDC) properly. I am fully aware of this and tried to take this into account in the Discussion section of the submitted manuscript. I also agree with referee 2, who stated that the BDC is simulated by the model but with the upper branch forced into the upper most levels.

After a brief description of the upper boundary condition, just to avoid misunderstandings, which may have occurred, I will outline the model's capabilities with respect to dynamics and ozone chemistry mean state, transient behaviour and variability.

Based on these arguments I will come to two main conclusions: 1 For a proper simulation of tropospheric and stratospheric ozone, a model is necessary which includes sufficiently well simulated tropospheric and stratospheric dynamics and chemistry and especially resolves well enough the transition between those areas. 2 As indicated by existing evaluation studies, the model E39/C is able to simulate most of the ozone mass correctly, in terms of mean state and variability and fulfils the above criteria.

Upper boundary conditions for the chemistry at 10 hPa:

In the uppermost level, which is centred at 10 hPa, total Cly and NOy is prescribed as a function of latitude and month. The partitioning, however, is simulated and not forced by the upper boundary.

All other species, like ozone, methane, nitrous oxide, water vapour, etc. have a zero upward flux boundary condition.

This implies that ozone changes at lower latitudes can propagate and do propagate to

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higher latitudes.

Dynamics

The ECHAM model in combination with the chemistry model CHEM has been used for more than 10 years. Numerous evaluation studies have been published, including inter-comparisons with observational data as well as middle atmosphere model data. Stratospheric dynamics and chemistry have carefully been validated with observations and other CCMs, including middle atmosphere models, in a variety of ways, which I will summarize in the following.

Polar vortex dynamics:

Grewe et al. (1998) showed in a detailed analysis of ECHAM3/CHEM, which was based on the 19 level version only, that the model is able to simulate a variety of dynamical situations. Vortex erosion caused e.g. by blocking of the flow by the Aleutian high pressure system, vortex splitting, deformation and displacement frequently occurs in the NH winter period, even in the coarser ECHAM3 resolution (vertical: 19 levels, horizontal: T21).

Wind and temperature anomalies

Hein et al. (2001) showed that the zonal wind is reasonably well simulated with a clear separation of the subtropical and polar night jet, clear inter hemispheric differences and a reversal of the zonal wind during summer. However, the tilts of the stratospheric jets show differences to the observations and the easterlies during summer do not penetrate deep enough into the lower stratosphere. Both effects are probably linked to the upper boundary since gravity wave effects (dissipation) in the upper stratosphere and mesosphere are not simulated, i.e. parameterised like in middle atmosphere models. The evolution of the wind field during the course of the year has been compared



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to NCEP data by Hein et al. (2001) at 60N 30 hPa. The extremely low variability during summer is well captured, also the extremely high variability during the end of the northern winter (Mar-May). However, the variability is reduced during early winter, e.g. Dec-Jan, where a variability of about 35 m/s is observed but only roughly 20 m/s simulated. In any case, the variability is large and produces minor warmings with a frequency of about 2 in warm winters. Indeed, major warmings, following the definition of a zonal wind reduction to less than 10 m/s at 30 hPa and 60N and a reversal of the temperature gradient between 60N and the Pole at 30 hPa occurs 5 times within 20 years of simulation (Hein et al., 2001). The increased vertical resolution at tropopause levels clearly increased the model's ability to reproduce the observed interannual and intraseasonal variability (Hein et al., 2001).

Impact of tropospheric variability on stratospheric dynamics

A prominent tropospheric variability pattern is the North-Atlantic Oscillation (NAO). Schnadt and Dameris (2003) showed that the stratospheric response of E39/C to the tropospheric North-Atlantic oscillation is well simulated in comparison with observations, with a strengthening (roughly 8 m/s increase in zonal wind speed) and cooling (roughly 8 K) of the polar vortex during positive NAO phase compared to negative NAO phase. The heat flux changes are comparable in E39/C and ERA data with respect to pattern and absolute numbers. This clearly indicates that the interaction between tropospheric wave forcing and stratospheric dynamics is reasonably well simulated, which is important to the variability of stratospheric ozone (see below). No indication is found that the upper boundary principally limits these results.

Subsidence

The cooling of the polar vortex results in a descent within the vortex. This has been estimated from various observations to be in the range of 0.05 to 0.08 cm/s at 50 hPa (see discussion Grewe et al., 1998). E39/C simulates values between 0.08 and 0.1 cm/s. This means that air masses which are located at 50 hPa at the end of the winter



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were found at around 20 to 10 hPa at the beginning of the winter, which still is within the model domain.

Residual streamfunction

Austin et al. (2003) compared a number of CCMs with respect to the residual streamfunction at 50 hPa. Since they addressed the issue of the upper boundary in detail I am happy to cite the relevant text passage: ' For the solstice periods, all the models have the same qualitative shape as the observations with a peak in absolute values occurring in the subtropics of the winter hemisphere. In the northern winter, the results of E39/C agree well with observations between 0 and 45 N but farther north the streamfunction reduces significantly, implying less downward transport. The MAECHAM/CHEM results agree better with observations in high northern latitudes, but there is no indication that this is a result of the higher boundary since the other models are more consistent with the values of the E39/C model in this regard. In the extra-tropics of the northern summer, the E39/C results are higher than observations and the other models, implying too much transport. Most models have the same problem, but to a varying extent in the southern summer. As in the northern winter, the streamfunctions of most models are smaller then observed in the southern winter, again indicating insufficient transport. Thus, the differences in the streamfunction between the MAECHAM/CHEM and E39/C results are not significantly more than between the other models. These two models have equivalent physics and chemistry, but the E39/C model has a lower upper boundary, with appropriate upper boundary condition for constituents and additional dissipation in the top layers. Thus, the dissipation may be more important than the position of the upper boundary in the determination of the residual circulation. During the equinox periods, the models are broadly consistent with each other. The E39/C model has slightly higher values of the streamfunction in mid-latitudes than other models, but this may be related to an extended winter regime in the model rather than direct effects of the upper boundary.'

Looking at the whole atmosphere, the pattern of the meridional stream function agrees



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well with analysis of observational data (Schnadt et al., 2002). The 50 hPa were taken to better quantitatively compare the results.

Tropical ascent

An important part of the BDC is the up-welling in the tropics. The 100 hPa upward mass flux for DJF and JJA is simulated to be 19.4 and 16.4 $10^9$ kg/s, respectively, which is higher than derived from observations (11.4 and 5.6 $10^9$ kg/s; UKMO; Rosenlof and Holton, 1993)and simulated with middle atmosphere models (13-16.2 and 7.9-9.8 $10^9$ kg/s, CCM2, Mote et al., 1994)(See Stenke, 2005).

Extra-tropical Subsidence

In agreement with the overestimated tropical lifting the extra-tropical downward mass exchange is slightly overestimated. Based on UKMO and MLS data estimates of 8.1 and 10.3 $10^9$ kg/s were given for the NH in DJF, whereas the model simulates 14 $10^9$ kg/s. In summer observational data give 2.6 and 0.5 $10^9$ kg/s and the model 5.7 $10^9$ kg/s.

Age of air

Based on the analysis of the meridional circulation, it becomes clear that the mean age of air, is underestimated. In fact, a detailed analysis shows for the tropics, e.g. at 10 hPa, that a mean age of air of 3 years, whereas from observations 3.5 years are derived.

It is important to note that although the BDC extends to high altitudes, the mass included in this circulation is decreasing exponentially.

Clearly, the low upper boundary of the E39 climate model resolves the dynamics differently to whole middle atmosphere models. However, none of the findings indicate that this upper boundary is a sustainable restriction to the model, which is limiting its use with respect to troposphere, lower and mid stratosphere dynamics. Even comparisons to middle atmosphere models didn't indicate that among the limitations of all these



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models, the upper boundary is an outstanding issue.

Ozone Chemistry

Vertical profiles

In a variety of papers ozone profiles have been validated (e.g. Hein et al., 2001; Gauss et al., 2005). The model E39/C is able to maintain large gradients of various species, e.g. ozone, near the tropopause due to the high vertical resolution (around 700 m) (Grewe et al., 2001). This clearly shows the advantage of an increased vertical resolution at the tropopause compared to many other models as well as the standard ECHAM4 model.

Impact of Warmings

As discussed above, the model is able to reproduce the frequency of minor and strong minor warmings as well as the impact of tropospheric variability (NAO) on stratospheric dynamics. This has clearly an impact on the ozone chemistry during NH winter periods and leads to a variability in total ozone columns of 15

Inter-hemispheric differences

In general, the polar processing of the chlorine species is well simulated in E39/C, e.g. with respect to the formation of reservoir species ClONO2 and HCl. During Northern Hemisphere winter activated ClOx is first converted into ClONO2 (including the formation of a chlorine nitrate collar, as observed), whereas during Southern Hemisphere winter the denoxification and denitrification inhibits the ClONO2 formation, so that first HCl is formed (Steil et al., 1998, Webster et al., 1993, Douglas et al., 1995).

Impact of variations in tropical ascent on ozone

The interaction between dynamics and ozone chemistry in the lower tropical strato-



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sphere, as simulated by E39/C, is thoroughly described in Stenke and Grewe (2005). After the eruption of the Pinatubo volcano, the tropical ascent is increased, which leads to a shift in the ozone profile in the region where dynamics control the ozone profile. The response in ozone is well simulated by the model E39/C compared to observations (Stenke and Grewe, 2005).

QBO and Solar cycle

Recently, Dameris et al. (2005) and Steinbrecht et al. (2005) presented an evaluation of E39/C (Steinbrecht et al. includes a comparison to the middle atmosphere version of ECHAM, MA-ECHAM4/CHEM) for a simulation period 1960 to 2000, with special emphasis on the variability of stratospheric ozone. Run with equivalent external forcings, both models revealed a good agreement with observational data throughout the period. The solar flux changes are inducing ozone changes, which are in the order of 3Similar results can be found with respect to QBO effects. Equatorial westerlies are correlated with positive ozone anomalies at tropical latitudes and high latitudes and negative ozone anomalies at mid latitudes. This pattern can be found in both model versions as well as in observational data.

Tropospheric impact on stratospheric ozone

A prominent tropospheric forcing (El Nino) was investigated by Steinbrecht et al. (2005): 'These ENSO anomaly patterns near the Aleutians indicate changes in the Aleutian tropospheric cyclone and stratospheric anti-cyclone that are correlated with ENSO. A generally stronger and more stable Arctic polar vortex during La Nina has been reported, e.g. in Labitzke and van Loon (1999). This is consistent with our findings, and has to be expected for the weaker Aleutian stratospheric anti-cyclone indicated by Fig. 10.'

Another important phenomenon, which is a combined effect of tropospheric and stratospheric dynamics, is the occurrence of so-called ozone miniholes. Poleward moving tropospheric tropical high pressure systems are accompanied by a high tropopause



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and lead to extremely low total ozone values especially when they are located below the polar vortex, because they induce a divergent stratospheric flow. Stenke and Grewe (2003) showed that this interplay of tropospheric and stratospheric dynamics on ozone is well simulated by E39/C in comparison to TOMS satellite data, in terms of location and seasonal cycle of occurrence: maximum occurrence is found over Europe, Greenland and North-west America with a peak in January and February.

These results indicate that the E39/C model is able to simulate tropospheric and stratospheric ozone with respect to a mean state but also and that is important in the context of the present paper, with respect to variability.

Steinbrecht et al. (2005) conclude: 'Despite its restriction to altitudes below 30 km, E39/C reproduces the observed variations surprisingly well. As expected from its extended altitude range up to 80 km, and its better representation of upper stratospheric and mesospheric processes like gravity waves, the MAECHAM4- CHEM simulation usually gives better agreement with the observations, especially for those variability patterns which include upper stratospheric/mesospheric processes.'

Based on these arguments I conclude:

1 For a proper simulation of tropospheric and stratospheric ozone a model is necessary, which includes sufficiently well simulated tropospheric and stratospheric dynamics and chemistry and especially resolves well enough the transition between those areas. Current chemistry-climate models have their drawbacks in this respect, but low model top is just one of them and not the outstanding one. E39/C fulfils the requirements.

2 As indicated by existing evaluation studies, the model E39/C is able to simulate most of the ozone mass correctly, in terms of mean state and variability. This implies that the model can be applied to the scientific questions raised in the manuscript. However, it is also obvious that the model has weaknesses, which have to be addressed and discussed. Apparently, this discussion ought to be improved, as suggested by both

reviewers.

References (* marks papers, which include a detailed validation of E39/C):

*Austin, J.; Shindell, D.; Beagley, S.R.; Brühl, C.; Dameris, M.; Manzini, E.; Nagashima, T.; Newman, P.; Pawson, S.; Pitari, G.; Rozanov, E.; Schnadt, C.; Shepherd, T.G., Uncertainties and Assessments of Chemistry-Climate Models of the Stratosphere, Atmospheric Chemistry and Physics 3, 1-27, 2003.

*Dameris, M. , Grewe, V., Ponater, M., Deckert, R., Eyring, V., Mager, F., Matthes, S., Schnadt, C., Stenke, A., Steil, B., Brühl, C. and Giorgetta, M. A. Long-term changes and variability in a transient simulation with a chemistry-climate model employing realistic forcing Atmospheric Chemistry and Physics 5, 2121-2145, 2005.

Douglass, A.R., M.R. Schoeberl, R.S. Stolarski, J.W. Waters, J.M. Russell III., A.E. Roche, and S.T. Massie, Interhemispheric differences in springtime production of HCl and ClONO2 in the polar vortices, J. Geophys. Res. 100, 13967-13978, 1995.

*Gauss, M. , Myhre, G., Isaksen, I. S. A., Collins, W. J., Dentener, F. J., Ellingsen, K., Gohar, L. K., Grewe, V., Hauglustaine, D. A., Iachetti, D., Lamarque, J. -F., Mancini, E., Mickley, L. J., Pitari, G., Prather, M. J., Pyle, J. A., Sanderson, M. G., Shine, K. P., Stevenson, D. S., Sudo, K., Szopa, S., Wild, O. and Zeng, G., Radiative forcing since preindustrial times due to ozone change in the troposphere and the lower stratosphere, Atmospheric Chemistry and Physics Discussions 5, 5751-5807, 2005.

*Grewe, V., M. Dameris, R. Sausen, and B. Steil, Impact of stratospheric dynamics and chemistry on Northern Hemisphere midlatitude ozone loss, J. Geophys. Res., 103, 25,417-25,433, 1998.

* Grewe, V., D. Brunner, M. Dameris, J.L. Grenfell, R. Hein, D. Shindell, and J. Staehelin, Origin and variability of upper tropospheric nitrogen oxides and ozone at northern

mid-latitudes, Atmos. Environ., 35, 3421-3433, 2001.

*Hein, R., M. Dameris, C. Schnadt, C. Land, V. Grewe, I. Köhler, M. Ponater, R. Sausen,. B. Steil, J. Landgraf, C. Brühl, Results of an interactively coupled atmospheric chemistry-general circulation model: Comparison with observations, Ann. Geophys. 19, 435-457, 2001.

Labitzke, K. and van Loon, H.: The stratosphere: phenomena, history, and relevance, Springer Verlag, Berlin, 197 pp., 1999.

Mote, P.W., Holton, J.R., and B. Boville, Characteristics of stratosphere-troposphere exchange in a general circulation model, J. Geophys. Res. 101, 3989-4066, 1994.

Rosenlof K.H. and J.R Holton, Estimates of the stratospheric residual circulation using the downward control principle, J. Geophys. Res. 98, 10465-10479, 1993

*Schnadt, C.; Dameris, M., Relationship between North Atlantic Oscillation Changes and Stratospheric Ozone Recovery in the Northern Hemisphere in a Chemistry-Climate Model. Geophysical Research Letters DOI:10.1029/2003GL017006, 2003.

*Steil, B., M. Dameris, C. Brühl, P.J. Crutzen, V. Grewe, M. Ponater, and R. Sausen, Development of a chemistry module for GCMs: first results of a multiannual integration, Ann. Geophysicae, 16, 205-228, 1998.

*Steinbrecht, W. , Haßler, B., Brühl, C., Dameris, M., Giorgetta, M. A., Grewe, V., Manzini, E., Matthes, S., Schnadt, C., Steil, B. and Winkler, P., Interannual variation patterns of total ozone and temperature in observations and model simulations, Atmospheric Chemistry and Physics Discussions 5, 9207-9248, 2005.

*Stenke, A., and V. Grewe, Impact of ozone mini-holes on the heterogeneous destruction of stratospheric ozone, Chemosphere 50, 177-190, 2003

*Stenke, A. and Grewe, V., Simulation of stratospheric water vapor trends: impact on stratospheric ozone chemistry, Atmospheric Chemistry and Physics 5, 1257-1272, 2005.

*Stenke, A., Stratosphärischer Wasserdampf in einem gekoppelten Klima-Chemie-Modell: Simulation, Trends und Bedeutung für die Ozonchemie, PhD., University Munich, submitted, 2005.

Webster C.R., R.D. May, D.W. Toohey, L.M. Avalone, J.G. Anderson, P. Newmann, L. Lait, M.R. Schoeberl, J.W. Elkins, and K.R. Chan, Chlorine chemistry on polar stratospheric cloud particles in the arctic winter, Science 261, 1130-1134, 1993.

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