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Atmospheric
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Discussions

Interactive comment on "Energetic particle precipitation in ECHAM5/MESSy1 – Part 1: Downward transport of upper atmospheric NO$_x$ produced by low energy electrons" *by* A. J. G. Baumgaertner et al.

A. J. G. Baumgaertner et al.

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We thank all referees for the detailed review of our manuscript. The constructive criticism and ideas presented are much appreciated.

Referee #1

Replies to General comments:

The referee mentions advantages and limitations of the presented simple parametrization. The revised manuscript will contain a more detailed description and discussion of the parametrisation and its limitations. For the Southern Hemisphere, the following

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is noted in the revised manuscript: "Randall et al. (1998), Randall et al. (2007), and Siskind et al. (2000) have described that A$_p$ is a good approximation for interannual variations of LEE NO$_x$ in the polar vortex. Neither seasonal nor interannual variations of the transport between the source region and the model top, i.e. the lower thermosphere (LT), can be captured if the A$_p$ index is used as the only input variable. Seasonal variations of this transport are in the model "parametrised" using the sinusoidal time dependency (Eq. 4). Interannual variations of transport in the LT are not considered, based on the fact that good agreement between interannual variations of A$_p$ and stratospheric NO$_x$ enhancements was found by the authors mentioned above, and because of the lack of a long term dataset for vertical transport in the LT. In the mesosphere, which is mostly captured by the model, and the stratosphere, variations in the strength of the Southern Hemisphere polar vortex are known to be small, but any interannual variations present in the model do not correlate with observed vortex strength because the model simulations presented here are not relaxed to observations. Other forcings such as sea surface temperatures and chemistry boundary conditions, are not sufficient to reproduce observed vortex variability, such as the sudden warming in 2002." We would like to stress that the parametrisation has been constructed such that the observed excess NO$_x$ matches the model excess NO$_x$ in the stratosphere, but not in the mesosphere. That means that the latitudinal extent of the injection area does not necessarily need to match the "real" extent. This is also partly true for the mesospheric vertical velocities. If they are significantly wrong, the amount of NO$_x$ deposited in the stratosphere will not be affected severely because the amount of NO$_x$ injected is chosen such that the correct amount is found in the stratosphere, although the timing of NO$_x$ deposition will be wrong, which will affect the overall ability of the parametrisation to reproduce observations.

For the Northern Hemisphere, additional aspects need to be considered: "The larger dynamical variability has an influence on the amount of LEE NO$_x$ deposited in the stratosphere (e.g. by Randall et al., 2005). Variability in the lower thermosphere is not captured in the model simulations and is thus potentially a significant error source.

Concerning the upper stratosphere and mesosphere, NO_x transport is exposed to the variability in the model. Therefore, if the model is free running and not reproducing observed dynamical interannual variations, the agreement between model and observed NO_x will be worse than by just comparing A_p and measured excess NO_x. On the other hand, if the model reproduces observed dynamical variability (e.g. by relaxing model meteorology to observed meteorology), the agreement between model and observed NO_x will be better than by just comparing A_p and measured excess NO_x. In the case of the presented model simulations, the model is forced with assimilated SSTs, an observed QBO, and observed solar UV radiation. It has been shown by e.g. Labitzke (2005) that solar and QBO forcing determine a significant fraction of interannual variability of the vortex, especially the number of mid-winter warmings. This implies that the interannual variability of the Northern Hemisphere vortex in the presented model simulations should show similar features as the observed variability. However, this is still under investigation and beyond the scope of this paper." Results from additional years and a comparison with HALOE NO_x mixing ratios will be shown in the revised manuscript.

An issue that also led to confusion is the time periods of the A_p index employed. Equation 1 was found by using May-July average A_p indices in an attempt to be able to neglect the influence of the seasonal variation of the vertical transport at that stage. However, of course a higher time resolution is desirable. Therefore, monthly values of A_p were used to find Eqs. (3) and (4). Strictly speaking, there has not been any evidence presented that monthly values of A_p also correlate with monthly LEE NO_x. However, it is very likely that LEE NO_x will follow geomagnetic activity also on shorter timescales than yearly. On the other hand, because of the transport timescales involved (assuming 1km/day, the transport e.g. from 110 km to 80 km would take 30 days), a resolution higher than approximately one month is also unlikely to improve the results, especially when no time lag between A_p and the corresponding NO_x injection is employed. This is now discussed in the revised manuscript. An additional figure showing the variation of the flux for the Southern Hemisphere winter 2003 using

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different types of time variability in Eq. (4) is shown in the supplement.

Replies to specific comments:

21202 l07: The paragraph has been extended and now reads: “The electrons originate at the sun and from magnetospheric reservoirs, and precipitate at high latitudes during times of enhanced geomagnetic activity. In terms of stratospheric NO$_x$ production, Funke et al. (2005) found electrons with energies up to approximately 30 keV, which deposit their energy above 90 km, to be the most relevant.”

21202 l23-26: References were added and the sentence now reads: “Since the 1980’s measurements and models have shown that under certain circumstances, NO$_x$ produced in the thermosphere by precipitating low energy electrons (LEE) can be transported downward into the stratosphere and there engage in catalytic ozone destruction (Brasseur and Solomon, 1986; Callis et al., 1998; Callis and Lambeth, 1998; Callis et al., 2001, 2002; Randall et al., 2007; Funke et al., 2005). “

21206 l18: “at 45 km” was changed into “below 45 km” as suggested

21207 l01: For Eq (2), the A$_p$ index was averaged over 2-week periods and $g = A_p^{2.5} * d * cm^{-3}$ was compared to yearly maximum values of R07 Fig 7 to yield d=2.20. The manuscript was changed accordingly: “Similar to above, the scaling function is derived using the data from R07. The A$_p$ index was averaged over 2-week periods and then $A_p^{2.5} \cdot a \cdot cm^{-3}$ was fitted to yearly maximum values of RO7 Fig. 7, reproduced here as Fig. 6, to yield $a = 2.20 \cdot 10^5$. Then excess NO$_x$ densities $g_{LEE-NOx}$ are

$g(A_p) = A_p^{2.5} \cdot 2.20 \cdot 10^5 cm^{-3}$. ”

21207 l05: Assuming an average vertical velocity would indeed be error-prone, which is why we chose to base this part of the parametrisation on results of test simulations. This is now explained in the revised manuscript: “For the flux calculation the following information are needed: (1) excess densities g, (2) an average vertical velocity, (3) a loss factor which accounts for transport out of the polar night region. Instead of

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making assumptions about the latter two, which would be error-prone, a trial-and-error approach was chosen in order to get results at 45 km that match observations. Therefore, a value for the combination of the latter factors was established through a series of test simulations. Several EMAC simulations with a variable factor c, see Eq. (3), were conducted for the year 2003 in lower vertical resolution with 39 levels (T42L39). Model excess NO_x densities at 45 km were calculated by subtracting densities from a reference simulation with the submodel turned off. Then, model excess NO_x were compared to the results of R07 (their Fig. 7)."

A scaling of the c-factor by the model vertical velocity at the uppermost layers is an interesting idea that might improve the results for the mesosphere if there is indeed a correlation between lower thermosphere vertical velocities and model vertical velocities. However, such investigations have not been conducted, but are expected to be performed in recently approved projects in the German CAWSES program.

"transport out of the vortex..." has been changed into "transport out of the polar night region." as suggested.

Variability due to transport out of the polar night is accounted for only below 80 km. We do not have the capabilities to asses the variability of the NO transport out of the polar night in the lower thermosphere, i.e. above our model top. Unfortunately, this means that we are not able to directly assess the error from this. However, in light of the observed correlation between the A_p index and stratospheric NO_x enhancements this does not appear to be a major factor in the Southern Hemisphere. In the added section on the parametrisation in the Northern Hemisphere this is mentioned as a possibly important error source.

21207 l07: Test simulations were conducted for Southern Hemisphere winter 2003 in lower resolution (T42L39, same model top height at 0.01 hPa). Excess NO_x was determined by subtracting NO_x densities from a reference simulation with the submodel turned off, and not by the technique from R07. This is now specified in the manuscript.

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21207 l8: “model $g_{LEE-NOx}$ at 45 km” was changed to “model excess NO$_x$ were compared to the results of R07 (their Fig. 7).”

21207 l16: The time dependence describing the seasonal variation of the flux in the upper mesosphere and lower thermosphere, i.e. between the source region and the model top, is ad hoc and the sinusoidal variation represents the minimal requirement of a seasonal variation with maximum in winter. The 10 This additional time dependence is certainly not an optimal approach, but since there are no long-term datasets available it would be difficult to improve this. Consistent models that cover the entire middle atmosphere and the thermosphere could be helpful, and such improvements can be expected from projects in the German CAWSES program but are far beyond the scope of this paper. For the Northern Hemisphere the time dependence is shifted by half a year.

21207: l20-22 The referee suggests to confine NO$_x$ deposit using equivalent latitudes. Equivalent latitude is poorly defined at 0.01 hPa, making this approach difficult. In addition, any NO$_x$ deposited outside the vortex in the current scheme, will be quickly removed by advection/diffusion to sun-lit areas as well as through mixing with low-NO$_x$ air coming from sun-lit latitudes. Therefore, the authors do not consider this a major error source in the parametrisation.

21207 l26: See the above discussion on timescales.

21208 l09-10: A more thorough discussion and evaluation of the Northern Hemisphere LEE NO$_x$ has been added to the manuscript, see above citation from the revised manuscript. Also, a comparison with HALOE in form of NO$_x$ histograms for geomagnetically quiet and active periods was added for the northern and Southern Hemisphere.

21209 l15-17: Comparing Fig 6 of F05 and Fig 3 of this paper is not a valid comparison because of the different temporal averaging and different horizontal and vertical coordinates. A more valid comparison in equivalent latitude and potential temperature coordinates was performed and added to the supplement. In the manuscript we added:

“Transformed onto equivalent latitude (see supplement) enhancements can be seen to reach as far south as 40S, similar to Fig. 6 of F05.”

21210 l09: “excellent agreement” was changed into “generally good agreement”. Concerning the August enhancement at 2500 K the following was added: A NO$_x$ enhancement centred around 2500 K in August is only found in the model results and does not appear in the MIPAS data. Examining the CO abundances inside the vortex, Fig. 2, reveals that in the model a strong descent of mesospheric air occurred during this time, leading to the NO$_x$ enhancements. The MIPAS CO measurements do not show this feature, explaining the difference between model and observed NO$_x$ at this time.

21210 l18: Corrected.

21210 l21-22: Corrected to “moderate dynamical conditions in the Northern Hemisphere, similar to those found in the 2002/03 winter”.

21211 l01: Average excess NO$_x$ was employed in the 1992-2002 simulation in order to avoid overestimation under all circumstances, since the simulation results are used for different analysis unrelated to LEE NO$_x$ (e.g. CCMVal, a project of SPARC/WCRP). The model simulation for the year 2003 was done independent of these projects.

21212 l16-19: The paragraph and corresponding Figure were removed.

21212 l25ff: For the revised manuscript, an additional simulation without EEP was performed for the year 2003 and is used for the comparison.

21213 l17: “monthly A$_p$ values” is correct, see the above discussion on timescales.

21206 l20: Corrected to $10^{-3} * 1GM$

21227 Fig 10: Figure removed in revised manuscript because no longer necessary (see comment 21212 l16-19)

Referee #2

Section 2.2 In the revised manuscript, the description of the submodel is more clearly separated between the northern and the Southern Hemisphere.

Concerning the period of A_p indices employed the description is make more clearly in the manuscript. Equation 1 was found by using May-July average A_p indices in an attempt to be able to neglect the influence of the seasonal variation of the vertical transport at that stage. However, of course a higher time resolution is desirable. Therefore, monthly values of A_p were used to find Eqs. (3) and (4). Strictly speaking, there has not been any evidence presented that monthly values of A_p also correlate with monthly LEE NO_x. However, it is very likely that LEE NO_x will follow geomagnetic activity also on shorter timescales than yearly. On the other hand, because of the transport timescales involved (assuming 1km/day, the transport e.g. from 110 km to 80 km would take 30 days), a resolution higher than approximately one month is also unlikely to improve the results, especially when no time lag between A_p and the corresponding NO_x injection is employed. The variation of the flux for the Southern Hemisphere winter 2003 using different types of time variability in Eq. (4) is shown in the supplement.

Later in section 2.2 For the Northern Hemisphere the time dependence is shifted by half a year. This is stated in the revised manuscript. The fitting was not done separately for the Northern Hemisphere.

Section 3: page 21210: Corrected to “exceed 45 ppbv”

page 21210, line 21-22: Corrected to “works well under moderate dynamical conditions in the Northern Hemisphere, similar to those found in the 2002/03 winter”.

page 21212, line 20: In fact, both LEE and SPE NO_x parametrisations were applied in all model runs. This will be discussed in more detail in the companion paper. Because the SPE submodel injects the NO_x directly into the stratosphere, and geomagnetic activity related enhancements take several weeks to reach the stratosphere, these two sources can be distinguished.

page 21212, line 25: For the revised manuscript, an additional simulation without EEP was performed for the year 2003 and is used for the comparison.

Technical corrections:

page 21203, line 2: The paragraph has been extended and now reads: “The electrons originate at the sun and from magnetospheric reservoirs, and precipitate at high latitudes during times of enhanced geomagnetic activity. In terms of stratospheric NO$_x$ production, Funke et al. (2005) found electrons with energies up to approximately 30 keV, which deposit their energy above 90 km, to be the most relevant.”

page 21203, line 8-9: Randall et al. (2007) referenced at this point in the revised manuscript.

page 21204, line 28: Corrected.

page 21205, line 23: NMHC given fully now.

page 21207, eq. 4: Variable d is now specified (day of year).

page 21210, line 12: Corrected to “F05 presented measurements...”

page 21210, line 17: Corrected to “descent”

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Referee #3

1) A discussion of downward transport in the model will be added in the revised manuscript by comparing model and observed CO mixing ratios throughout the polar middle atmosphere.

2) Statement on ozone was removed for the revised manuscript.

3) The referee suggests to confine NO_x deposit using equivalent latitudes. Equivalent latitude is poorly defined at 0.01 hPa making this approach difficult. In addition, any NO_x deposited outside the vortex in the current scheme, will be quickly removed by advection/diffusion to sun-lit areas as well as through mixing with low-NO_x air coming from sun-lit latitudes. Therefore, the authors do not consider this a major error source in the parametrisation.

4) This paragraph was rewritten according to the suggestions of referees 1 and 3: “From the model results in Fig. 5b (revised manuscript) the downward transport of a NO_x enhancement exceeding 45 ppbv in June/July is clearly discernible and is generally in good agreement with the MIPAS observations (Fig. 5a) with respect to magnitude, timing, and altitude of the enhancements. A NO_x enhancement centred around 2500 K in August is only found in the model results and does not appear in the MIPAS data. Examining the CO abundances inside the vortex, (see figures in revised manuscript), reveals that in the model a strong descent of mesospheric air occurred during this time, leading to the NO_x enhancements. The MIPAS CO measurements do not show this feature, explaining the difference between model and observed NO_x at this time. A NO_x enhancement centred around 2500 K in August is only found in the model results and does not appear in the MIPAS data. Examining the CO abundances inside the vortex, Fig. 2 (see revised manuscript), reveals that in the model a strong descent of mesospheric air occurred during this time, leading to the NO_x enhancements. The MIPAS CO measurements do not show this feature, explaining the difference between model and observed NO_x at this time.”

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5) We added: “Note that the nighttime MIPAS NO_2 only represent a lower limit for NO_x.”

The paragraph was rewritten to: “Both the model and observations show a strong descent of NO_x starting at 3000 K in November, with mixing ratios of more than 16 ppbv. The excess NO_x is transported down to altitudes of 1500 K (40 km) during the following two months. A second strong enhancement observed by MIPAS in December is not captured by the model. In February, both model and observations again show enhancements above 2500 K, exceeding 16 ppbv in the observations and reaching 10 ppbv in the model. Because of the fact that the main features of the observed NO_2 enhancements are reproduced, we conclude that the parametrisation also works well under moderate dynamical conditions in the Northern Hemisphere, similar to those found in the 2002/03 winter. “

6) In the revised manuscript, the ozone loss is now calculated from the difference between a simulation with the submodel turned on and one with the submodel turned off. In addition, a comparison of total column ozone was added.

Minor comments:

1) The following was added to the introduction: “In addition to geomagnetic activity, meteorological conditions can have a significant effect on the amount of NO_x found in the polar stratosphere. A stronger and better isolated polar vortex enhances the descent of NO_x from the mesosphere and thermosphere. Especially in the Arctic, where dynamical variability is greater than in the Southern Hemisphere, this can occasionally lead to pronounced NO_x enhancements that are not linked to geomagnetic activity, as has been shown by Randall et al., 2006.”

2) We added “..., derived there from deviations from the standard low NO_x versus low CH_4 relation.”

3) “The vortex edge was defined using the Nash criterion.” added to all relevant figures.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 21201, 2008.