

Interactive comment on “A model study of the January 2006 low total ozone episode over Western Europe and comparison with ozone sonde data” by A. Mangold et al.

A. Mangold et al.

Received and published: 10 July 2009

First of all, we would like to thank very much the referee for the very constructive and helpful comments, which helped to improve the manuscript.

Specific comments:

Referee: The separation of contributions (1) and (2) is limited as pointed out by the authors (p6023 I20/21). Furthermore, there is no separation of the effects within (2), i.e. the horizontal advection of ozone-poor low-latitude air and the uplift of isentropes. Such a separation is done eg. in Koch et al. (2005). It would be a second relevant output of the paper to distinguish both effects, since Koch et al. (2005) found in a climatology that vertical displacement of isentropes is less important than horizontal

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advection, whereas James et al. (2000) found the opposite. Such a separation will also help to separate the contributions (1) and (2) better. I strongly recommend to perform this additional effort.

Answer:

We performed an analysis of the ozone loss due to the vertical displacement of isentropes and pressure change within the altitude compartment $\Theta = 300\text{--}450$ K. This analysis and its results necessitated a restructuring of section 6.2 Quantification of responsible mechanisms for the ozone decrease. There are now three subsections:

6.2.1 Contribution of the dynamic mechanisms below and above $\Theta = 450$ K; comprising everything from p6022, line 27 to p6024, line 25, plus p6025, line 22 to p6026, line 20.

6.2.2 Influence of uplift of isentropes and pressure change; comprising the results of the additional analysis (see text below). There is also a new Table 6.

6.2.3 Impact of chemistry; comprising everything from p6024, line 26 to p6025, line 21, including the former Table 6, which is now Table 7.

Text new subsection 6.2.2 Influence of uplift of isentropes and pressure change:

In order to better separate the contributions of horizontal and vertical transport processes to the low total ozone event, the effects of advection of ozone-poor low-latitude air masses and vertical displacement of isentropes were distinguished within the layer $\Theta = 300$ to 450 K. To this end, the respective ozone column decrease caused by the pressure change on isentropes was investigated.

To estimate that influence, mean ozone mixing ratios (calculated from the respective ozone soundings in January 2006 before the event, at the six stations) on the six Θ -levels between $\Theta = 300$ to 450 K were converted to partial pressures using the actual pressure on the respective isentrope on the respective day of observed minimum total ozone. Whereas the mean ozone mixing ratios were always the ob-

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served ones, the actual pressures were taken from the soundings and the models, respectively, in order to estimate specifically the pressure impact for both the observations and the models. These converted ozone partial pressures were subtracted from the partial pressures calculated with the respective observed mean pressures on the Theta-levels. The difference was then converted to Dobson Units and compared to the measured ozone column decrease on the Theta-levels. Finally, we calculated for both soundings and models the overall (i.e. the average from the six Theta-levels) percentage contribution to the ozone column decrease within the layer Theta = 300 to 450K (see Table 6).

This percentage contribution varied between 26% (Payerne, E5/M1) and 72% (De Bilt, CLaMS). The influence of pressure change was weakest at Payerne (mean = 31%) and strongest at De Bilt and Lerwick (62% and 57%, respectively). In general, the three models revealed higher contributions than observed by the ozone soundings. This can be explained by differences between modelled and observed pressure fields. The overall mean contribution of pressure change to the ozone column decrease, calculated from ozone soundings and models, is 46%. That influence of the pressure change was not constant over height. In the layer Theta = 300 to 400K, the mean contribution was 31%, whereas it was 66% within Theta = 400 to 450K. This indicates that the advection of ozone-poor low-latitude air masses had its strongest impact around the tropopause and in the lowest part of the lower stratosphere.

The mean contribution at the respective stations (see Table 6) was then taken to calculate the respective fraction in DU of the observed integrated ozone column change in the layer Theta = 300 to 450K (see Table 5). This amount in DU was then compared to the total ozone column reduction at the respective station. It became obvious that the influence of pressure change on isentropes contributed between 10% (De Bilt) and 16% (Hohenpeissenberg) to the total ozone column reduction. Compared to the horizontal transport processes (i.e. advection of ozone-poor low-latitude air masses and displacement of the polar vortex), the influence of vertical transport processes was

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therefore only of minor importance.

That additional analysis triggered further additional statements and corrections:

Abstract, p6004, lines 19 to27 changed to:

This analysis demonstrated that mainly the displacement of the ozone depleted polar vortex contributed to the ozone column decrease. Advection of ozone-poor low-latitude air masses was important in the UTLS region. The vertical displacement of isentropes connected with divergence of air out of the column was found to be of minor importance compared to the horizontal transport processes. Severe low total ozone episodes seem to occur when the mentioned mechanisms are superimposed. Instantaneous, in-situ chemical ozone depletion accounted for only 2 +/-1% of the overall total ozone decrease at the sounding stations.

Discussion, p6030, line 3, statement added:

Our results, however, revealed that in the UTLS region the impact of vertical displacement of isentropes and advection of ozone-poor air masses were almost equally important. Our analysis is consistent with Koch et al. (2005) who found that the vertical transport processes provided an additional but less important contribution to low total ozone events compared to horizontal transport processes.

Conclusions, p6032, line 21 to p6033, line5, paragraph changed to:

In Fig. 15, Table 5 and Table 6, the dynamic processes responsible for the evolution of the low total ozone event are quantified for the sonde measurements and the model results. The displacement of the ozone-depleted polar vortex caused around 80% of the total ozone column reduction at De Bilt and Lerwick, and on average 70% at Uccle. Over Prague, Payerne and Hohenpeissenberg that influence was less dominant. It accounted for around two-thirds over Prague, 60% over Payerne, and 55% over Hohenpeissenberg. The influence of vertical transport processes (pressure change on isentropes within $\Theta = 300$ to 450K) contributed between 10% (De Bilt) and 16%

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(Hohenpeissenberg) to the total ozone column reduction and was therefore only of minor importance. The advection of ozone-poor low-latitude air masses had its strongest impact around the tropopause and in the lowest part of the lower stratosphere. Taking into account the error estimate for the total ozone change (15 to 25%), and the uncertainties related to the calculation of the reference profiles and the delimitation of the two altitude compartments, only at De Bilt, Lerwick, and Uccle the dominance of the polar vortex influence was significant.

Conclusions, p6033, line 27 to p6034, line6, paragraph changed to:

This analysis demonstrated that mainly the displacement of the ozone depleted polar vortex contributed to the very low total ozone episode in January 2006. Vertical transport processes were found to be only of minor importance compared to the horizontal transport processes. However, statistically significant was only the dominant polar vortex influence at Lerwick, De Bilt and Uccle. Thus, which mechanism is dominant at a certain location will depend on meteorology and the relative position of the location to the forcing dynamics. This underlines the high spatial and temporal variability of the total ozone column. Severe low total ozone episodes seem to occur when the mentioned mechanisms are superimposed.

Referee:

At p6029 l19 the authors cite Hood et al. (2001): "In the case of extreme minima, contributions from vertical transport processes contributed between 20 and 80 DU, ...". I don't find that statement in Hood et al. (2001) in particular not the value 20 DU.

Answer:

The value of 20 DU is indeed erroneous, we apologise for that. However, the respective statement in Hood et al. (2001) can be found in their section 3, Comparisons with other extreme ozone minima, on page 20,936. It mentions a possible contribution of around

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80 DU to the ozone minima by vertical transport processes. P6029, lines 18-20 are changed to:

In the case of extreme minima, vertical transport processes contributed around 80 DU and horizontal transport processes between 60 and 100 DU to the ozone minima.

Referee:

After referring to the effect of horizontal transport processes the authors continue to claim: "This is in good agreement with our findings that these two mechanisms are often of about the same magnitude, but varying from one location to the other, one mechanism can dominate." Hood et al. (2001) refer mainly to lower stratospheric transport effects not to vortex displacements. However, the authors don't separate these two effects, horizontal (lower stratosphere) and vertical transport processes, in their study. How can they claim that Hood et al. (2001) findings are in good agreements with their own ones?

Answer:

Our statement was made in view of the (however erroneous, see former comment) statement that vertical transport processes contributed between 20 and 80 DU. As process (2) of our article could be principally separated in a vertical and a horizontal contribution (however, we did not do it at that moment), we assumed, within the margin 20 to 80 DU, that part of the found ozone column change due to process (2) could be assigned to vertical processes and the other part added to the overall horizontal processes (including polar vortex shift). That assumed, our values of the ozone column change for processes (1) and (2) fitted in the boundaries of Hood et al. (2001) of 60 to 100 DU (horizontal) and 20 to 80 DU (vertical). In view of the performed separation of process (2), p6029, lines 18-22 are adapted as follows:

In the case of extreme minima, vertical transport processes contributed around 80 DU and horizontal transport processes between 60 and 100 DU to the ozone minima. This

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study, however, found distinctly lower contributions to the low total ozone event by the vertical displacement of isentropes.

Referee:

The authors have been put much effort in showing that instantaneous, in-situ chemical ozone depletion is negligible. In fact a simple estimation would do the same job. On page 6025 the authors give already an estimate of 5 DU ozone loss within days under extreme conditions. That would be Antarctic conditions during August/September. Since the winter was a rather warm winter and we have a mid January event the result of a much smaller instantaneous loss is not surprising.

Answer:

Indeed, we did not expect to find a large contribution of chemical ozone depletion to the event. However, we are convinced that investigating and quantifying the possible impact of chemical ozone depletion on that event adds to the general knowledge about ozone mini-holes, as there are not many studies analysing specifically that point of these events. Furthermore, from the temperature profiles of the soundings there were indications that PSCs could have formed.

Referee:

Why have the output of two different models been used to show and explain the instantaneous losses (Figs. 12 and 13)?

Answer:

The reasoning was that the two independent models could support each other. However, the cumulated chemical ozone change was readily available only from KASIMA, not for E5/M1. In the revised version of the manuscript, in Figure 13 now also E5/M1 results for CLOx are shown (see also our answer on comment 6 of Referee #2).

Referee:

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E5/M1 shows that practically all Cly, which is usually estimated to be in the order of 3.2 - 3.7 ppb, had been activated. However, KASIMA shows that only less than 1 ppb Cly had been activated. Where is the rest? That doesn't fit together. Obviously, the chemistry part of the models is not good enough to provide any estimate of the ozone loss.

Answer:

We analysed in more detail the active chlorine of both models. E5/M1-results for ClOx are now shown in Figure 13. Indeed, E5/M1 revealed more ClOx than KASIMA. We rewrote accordingly the respective section 5.3 Chemical species (see below). Nevertheless, we consider the chemistry part of the models as well suited to investigate possible ozone depletion. There is a recent paper (Khosrawi et al., 2009), showing that CLaMS, KASIMA and E5/M1 are in good agreement with Odin/SMR and ILAS/ILAS-II satellite ozone retrievals. The differences are generally in the range of +/- 20%. However, the authors found an underestimation of polar winter ozone loss both in KASIMA and E5/M1. We add this finding and reference in the discussion section, p6028, line 27, replacing the last sentence of the respective paragraph and also the Khosrawi et al. (2005) reference:

Recently, Khosrawi et al. (2009) showed that CLaMS, KASIMA and E5/M1 are in good agreement with Odin/SMR and ILAS/ILAS-II satellite ozone retrievals. Differences were generally in the range of +/- 20%. However, the authors found an underestimation of polar winter ozone loss both for KASIMA and E5/M1.

Referee:

It adds to my opinion that many phrases in the manuscript emphasizing that the models agree "very well" with the measurements at least with respect to chemistry, eg. when looking at Fig. 11, are too optimistic and should be avoided.

Answer:

We have adapted the optimistic statements where appropriate. Please see our respective answer to Referee #2, comment 8.

Referee:

The reason the authors deal with instantaneous losses is due to the fact that in this case the vertical uplift triggered PSC formation followed by chlorine activation. Therefore, they are interested in the ozone loss within 2 days due to this additional chlorine activation. If this is really interesting enough, one should at least mention that chlorine could have been activated before. Fig. 12 and the general meteorological situation of the whole winter support that chlorine had been activated.

Answer:

Indeed we consider it interesting to analyse the instantaneous chemical ozone loss, see also our answer further above. But, the referee is right that chlorine was also activated before that low total ozone event, as our KASIMA and E5/M1 analyses showed (E5/M1 revealing stronger activation than KASIMA). For January 2006 there was always active chlorine between $\Theta = 450$ and 550 K (or around 20.5 to 23.5 km for KASIMA) within the polar vortex, however distinctly lower after 21 January. The comment is addressed in the rewritten section 5.3 Chemical species as follows:

Further analyses of KASIMA and E5/M1 revealed that, before the low total ozone event took place, within the polar vortex there was always active chlorine between $\Theta = 450$ and 550 K.

Referee:

The sentence at p6019 l28: "If chemical ozone destruction by active chlorine had indeed happened during the low ozone episode, this would be indicated by a distinct reduction of the reservoir gases and a distinct increase of ClOx." is not correct. Ozone loss happens when ClOx is available and is not dependent on increasing levels.

Answer:

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The sentence within the rewritten section 5.3 Chemical species is now as follows:

If chemical ozone destruction had indeed happened during the low ozone episode, this would be indicated by available active chlorine.

Referee:

The authors mention several times the ozone depleted vortex and provide some references. On the other side they also note that the winter was one of the mildest on record and cite WMO (2006) stating overall column loss in the order of 13%. Although the statement is correct that in the vortex ozone had been depleted, the statement implicitly suggest that this is the main reason for low ozone within the vortex and/or the low total ozone event which is not the case. This should be emphasized in the text at least once.

Answer:

We added a sentence on p6029, line 12:

However, it is important to stress that the chemical ozone depletion within the vortex was not the main reason for the formation of the low total ozone event. The event was caused by horizontal and vertical transport processes and only marginally by chemistry.

As many comments refer to section 5.3 Chemical species, this section is rewritten as follows:

In order to evaluate the possibility of a contribution of instantaneous, in-situ chemical ozone depletion to the very low total ozone episode, KASIMA results for simulated active chlorine (ClO_x , i.e., $\text{Cl} + \text{ClO} + 2 \times \text{Cl}_2\text{O}_2$) and ozone variation due to chemistry (i.e., also non-halogen reactions taken into account) are shown in Fig. 12. These KASIMA ozone variations are the cumulated chemical changes of ozone over 24 h at each model grid point. Changes induced by transport are neglected. In Fig. 13, E5/M1 results for simulated mixing ratios of active chlorine and the reservoir gases HCl and ClONO_2 are presented. Active chlorine in E5/M1 comprises Cl, ClO, $2 \times \text{Cl}_2\text{O}_2$, HOCl,

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OCIO, and $2 \times \text{Cl}_2$. If chemical ozone destruction had indeed happened during the low ozone episode, this would be indicated by available active chlorine.

Considering the evolution of active chlorine between 17 and 20 January, represented by ClO_x at 23.5 km altitude (KASIMA) and $\Theta = 500 \text{ K}$ (E5/M1), it clearly can be seen that a layer of active chlorine moved over the sounding stations. KASIMA simulated a peak of ClO_x around 18 and 19 January, corresponding nicely with the region of adiabatic uplift and thus cooling of air masses. The simulated chemical ozone change (Fig. 12, bottom row) revealed in good agreement with the ClO_x results an increasing (17, 18 January), peaking (19 January) and decreasing (20 January) chemical ozone reduction over the same region. On the contrary, E5/M1 simulated not only higher ClO_x mixing ratios, but also the area of active chlorine filled nearly the whole vortex.

Further analyses of KASIMA and E5/M1 revealed that, before the low total ozone event took place, within the polar vortex there was always active chlorine between $\Theta = 450$ and 550 K . Before 17 January and after 20 January, KASIMA simulated between 0.1 and 0.3 ppbv ClO_x at the $\Theta = 500 \text{ K}$ level at the six stations. These values increased to around 1.0 ppbv during the event. Before 17 January and after 20 January, E5/M1 simulated similar, but slightly higher ClO_x values than KASIMA. During the event, E5/M1 modelled between 1.9 and 2.2 ppbv active chlorine at $\Theta = 500 \text{ K}$ above the stations. At the other altitude levels, the ClO_x mixing ratio and also the chemical ozone reduction levels were distinctly lower. The discrepancy between the models might mainly be explained by the different nudging schemes leading to slightly different dynamics in the models and different chemistry schemes (e.g., calculation of the actinic fluxes), causing differences in chlorine activation.

As active chlorine was always present within the vortex, it is interesting to investigate the possibility of additional chlorine activation during the low total ozone event due to the vertical uplift of isentropes (triggering cooling and possible PSC formation). The evolution with time of the reservoir gases ClONO_2 and HCl for the $\Theta = 500 \text{ K}$ level, as simulated by E5/M1, are shown in Fig. 13. Similar to the KASIMA simulations

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for ClO_x and the chemical ozone change, the area distinctly depleted of the reservoir gases moved from the North Atlantic towards Eastern Europe, corresponding again nicely with the region of adiabatic uplift and thus cooling of air masses. The reduction of the chlorine reservoir gases and therefore the liberation of active chlorine increased towards 19 January 2006, reaching a peak on that day and decreasing afterwards. As the release of chlorine on stratospheric cloud particles largely follows the reaction ClONO₂ + HCl - > Cl₂ + HNO₃, (e.g., Solomon, 1999), it is not surprising that the area of depleted ClONO₂ and HCl agreed very well. Both ClONO₂ and HCl were reduced to 10 to 20 pptv over Western Europe.

These findings indicate that indeed additional chlorine activation occurred as a consequence of adiabatic uplift, inducing a local and short-term, additional in-situ chemical ozone depletion around 19 January. The total simulated chemical ozone change (maximum between -40 and -30 ppbv / 24 h on 19 January at 23.5 km) is, however, far from being sufficient to explain the observed extreme ozone decrease around that date (see Figs. 2 and 3).

Referee - Technical corrections:

p6009 I12: I suggest to write: "The vertical resolution is in the order of 100 m." unless a good reference is given. The vertical resolution is usually dependent on the operation procedures and may even vary between BM and ECC sondes.

Adapted accordingly

p6009 I26: Why haven't data before the Pinatubo eruption been used?

The reference profile is intended to represent conditions of the stratospheric ozone layer not affected by volcanic eruptions. Before the Pinatubo eruption there have been other major volcanic eruptions affecting the stratosphere (e.g., El Chichon 1982). In addition, we consider the 12 year time period 1995-2006 as adequate for our purposes.

p6012 I4: photolysis

corrected

p6025 I3: Article Harris et al. (2002) does not exist.

We apologize for this error. In fact, the authors list is correct, but title and journal have been mixed up with another article. The correct reference is: Harris et al., Comparison of empirically derived ozone losses in the Arctic vortex, *J. Geophys. Res.*, 107(D20), 8264, doi:10.1029/2001JD000482, 2002. The reference list is adapted accordingly.

Fig. 1: Senseless legend to "Brewer (last year)" given.

The legend Brewer (last year) is omitted. At making this correction, we adapted also the plot title from Brewer #016 total ozone - Daily mean values Year 2006 to Total ozone at Uccle - Daily mean values. Legend Brewer (this year) is changed to Brewer (2006). Legend Dobson 2sigma year-to-year is changed to Dobson 2sigma interannual. Legend Dobson 2sigma total is changed to Dobson 2sigma overall (see also comment 3 of Referee #2).

Fig. 2 & 3: Both blue colors are hard to distinguish.

The figures are adapted. Instead of violet for the 20th (Uccle) and 14th (Payerne) January, the colour is now pink. It is now better distinguishable from the blue, black lines, and also from the red lines (especially in the middle stratosphere). As in Fig. 4 the same colour codes are used, the figure is adapted accordingly.

Fig. 3: Why is the Uccle mean given as a reference and not a Payerne mean? A Payerne mean would make more sense.

It is our intention to show a long-year mean as a reference profile. Indeed, the availability of a long-year mean also for Payerne would have been preferable. However, this would raise the need to assure the homogeneity of the time series, like it has been done for Uccle, but what is beyond the scope of this study. We could have plotted the mean profile from all January 2006 Payerne soundings before the low total ozone event. But then plotting reasonable standard deviations would not have been possible. Therefore,

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the Uccle long-year mean profile in Fig. 3 is intended to give an approximation of a Payerne reference profile.

Figs.: In general all writings in the figures should be easily readable (big enough) in a printed version. Currently, e.g. the numbers on the axis in Fig. 15 are hard to read and a minus sign in Fig. 12 does not show up in my print version at least.

In all figures the writings in the graphs and for the colour bar have been enlarged. At that occasion, in Figs. 2, 3, 4 some texts were changed for better readability after enlargement: Tropopause (WMO) to Tropopause, and Mean January 95-06 and Uccle January 95-06 to Uccle Mean. In the figure captions the respective explanations are still given.

References:

Khosrawi, F., Müller, R., Proffitt, M. H., Ruhnke, R., Kirner, O., Jöckel, P., Grooß, J.-U., Urban, J., Murtagh, D. and Nakajima, H., Evaluation of CLaMS, KASIMA and ECHAM5/MESSy1 simulations in the lower stratosphere using observations of Odin/SMR and ILAS/ILAS-II, Atmos. Chem. Phys. Discuss., 9, 1977-2020, 2009.

[Interactive comment on Atmos. Chem. Phys. Discuss., 9, 6003, 2009.](#)

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