Response to reviewer #1

We thank Ivanka Stajner for her insightful comments on the paper. We found of particular interest the hint to the predictability diagnostics in *Stajner et al. (2006).* In response to this reference and comments by reviewer #2, we are going to expand the section on the chemical predictability of the ozone hole by showing a graph of the bias development of the chemically initialized forecasts (FC15).

Further, we would like to report that we revisited the MOZART3 code after being granted an three-month extension of the response period. With the updated version we could achieve an improved simulation of the ozone hole. This has an impact on the errors of the stand-alone runs and the initialized forecasts (FC and FC15) but not on the analyses, since they are, as shown in the paper, controlled by the assimilated observations. We believe that the main findings of the original paper remain valid. The main improvement is that the MOZART full chemistry scheme is not outperformed by the simplified schemes anymore.

The discussion of the improvements of the MOZART-3 simulation and the extended discussion of the predictability can be found in the response to reviewer#2.

<u>Response to specific comments</u>

P. 9175, l. 24: MLS limb-viewing geometry may be the most important factor: Due to unique meteorology of the polar vortex even assimilation of very sparse POAM data was shown to substantially improve fidelity of ozone hole representation (Stajner and Wargan 2004).

We agree that the limb-viewing geometry is the most important contribution to the quality of the analysis profiles. During polar-night, the fact that MLS does not depend on sun-light is also very beneficial.

P. 9176, l. 24: Please give full names for MOZART-3, TM5, KNMI, GEMS. Also, P9181, l. 1: CBM4

We will include the full names in the text.

P. 9178, l. 9: Stajner et al. (2006) showed improvements in prediction of ozone in middle latitudes over several days from well-captured dynamical variability and improved initialization of ozone values in the polar vortex due to assimilation of ozone data from solar occultation instruments.

We will include this useful reference in the manuscript. The discussion of the predictability will be expanded as suggested by reviewer #2 (see response to reviewer #2). Further, we will discuss a new figure showing the RMSE with increasing forecast time for the three chemistry schemes and a tracer run without chemistry.

P. 9178, l. 11: Ozone chemical lifetime in the lower stratosphere can be on the order *of several months (e.g. Coy et al 2007)*

We could not find a respective statement in Coy et al. 2007. We will add the reference as another example of a data assimilation study using different ways to account for chemistry (i.e. no chemistry vs. a linear scheme). Following reviewer #2, we will the reformulate and add a reference of a model simulation.

"The chemical lifetime of ozone in the stratosphere varies with height from a couple of hours in the upper part to a couple of month in the lower part as simulated by two-dimensional CTMs (e.g., Figure 6 in Gray and Pyle at al., 1989)."

P. 9178, l. 20-24: Biases may not be due to chemistry. Note other common dynamical error contributions: excessive downwelling in the polar vortex, "leaky tropical pipe", excessive mixing across the polar vortex boundary, excessive stratosphere-troposphere exchange: : : Suggest rewording to: Biases in simulated ozone concentrations are due to accumulation of chemical and dynamical biases.

We agree that mentioning only excessive mixing (van Noije et al., 2004) is not sufficient. We will re-formulate:

"Biases in simulated ozone concentrations are due to the accumulation of chemical biases and biases because of errors in resolved-scale and sub-scale transport processes (van Noje et al., 2004, Rind et al. 2007)."

P. 9179, l. 13: Please provide model horizontal and vertical resolution and vertical extent.

The model resolution is given in section 2.4.

P. 9180, l. 11: Clarify if c1, ..., c5 are global constants. How is the dependence on T<195K and sunlight needed for ozone destruction expressed in this formula?

We include the following clarification:

.... (Cariolle and Teyssedre, 2007, version 2a). The coefficients c_1, c_2, c_3 and c_4 vary monthly and are given for different latitude and pressure levels. The formulae includes a parameterization of the rapid ozone loss due to the chlorine catalytic cycle which is based on a prescribed global equivalent chlorine content $\overline{Cl_{eq}}$ of 3.31 ppbv. The coefficient c_5 is non-zero only at temperatures below 195 K in daylight conditions. Its non-zero value corresponds to an e-folding time of about 2 days.

P9181, l. 13: Provide a brief description of the 4D-Var method and a reference to a full description.

We will reformulate the in the following way.

“The ozone satellite observations were assimilated by ECMWF’s incremental formulation of the four-dimensional variational data assimilation (4D-Var) method. A description of the 4D-VAR data assimilation algorithm of the IFS is given by Mahfouf and Rabier (2000) and with focus on the assimilation of aerosol in Benedetti et al. (2009). In 4D-Var, a cost function is minimised over a time window in such a way that the resulting analysis is an optimal combination of the model fields and the observations. Pre-scribed model and observation error statistics determine how much weight is given to the modelled and observed values in this combination. The minimisation over a time window makes it possible to take into account more observations as in the instantaneous case (3D-VAR).”

P9182, l. 19: Describe horizontal and vertical resolution of the assimilated observations.

We will include the following:

“The horizontal resolution of MLS is about 200–300 km and the vertical resolution is about 3 km in the range from 0.1 hPa to 215 hPa. The horizontal resolution of OMI is 13 x 24 km and that of SCIAMACHY is 30 x 60 km. The MLS resolution is about 2 – 3 times coarser in the horizontal and about 2 time coarser than the resolution of the assimilating model. The horizontal resolution of OMI and SCIMACHY is about 8 and 3 times finer than the IFS resolution of about 120 km.”

P9182, l. 26: What kind of algorithm is used for the pseudo-random thinning?

We will include the following to clarify the thinning process:

“The thinning algorithm takes the first observation which is not closer than half a thinning-grid box length from the selected observation in neighboring grid boxes. The randomness is achieved by the variable mapping between the model grid and the orbit location.”

P9183, l. 9: How does data resolution compare to model resolution? Why were only OMI and SBUV observation errors changed to account for representativeness error?

See above for the relation between the resolution of model and observations.
The setting of the error statistics have been obtained from ECMWF operational ozone analysis. Setting a lower limit (10%) for the observations error helps to avoid instabilities during the minimization caused by very low observation errors. The SCIAMACHY error data tend to have higher minimal error values which do not make it necessary to increase them. The representativeness error is difficult to quantify but should be considered for observations with a high resolution such as OMI.

P9183, l. 19: Please explain what is meant by ”without retrospective corrections”.

Some of the SBUV data have been identified as sensor fault (see p 9184 l 8). We assimilated these data in all experiments since they had been assimilated in the original NRT experiment. We will delete “without retrospective corrections” to avoid confusion.

P9184, l. 7: Quantify the missing tropospheric column.

The difference between the integrated MLS column and the total column observations ranged between 18 - 22 DU. We therefore rephrase as follows

“.. by about 50DU until this point in time. About half of this difference was caused by the fact that MLS observed the area poleward to 82° S all the time. It was therefore able to capture a larger proportion of the ozone hole. The missing tropospheric contribution, i.e. below 215 hPa, in partial columns in the MLS data (see Table 1) contributed about 18-22 DU.”

P9184, l. 12: Is the “diurnal variation” due to zonal asymmetry of ozone in the collar region around the ozone hole, with a climatological ozone maximum south of Australia?

Yes - the diurnal variation is mainly caused by the *zonal asymmetry of ozone hole.*
We will add:
“ … led to a diurnal variation of up to 50DU, which was caused by the the zonal asymmetry of ozone hole .

P9184, l. 13: Were “faulty data” eliminated by the quality control prior to assimilation?

The “faulty data” mentioned here were not eliminated by the quality control.

P9184, l. 20: What partial columns are integrated for the comparisons in Figs. 2 and 3?
For Figure 2 the MLS and SBUV-2 partial column were added to one column ranging from to 215 hPa for MLS or to 1013 hPa for SBUV.
Figure 3 shows the histograms of the departures in respect to the individual total MLS partial columns. Please note that the y-axis scale for MLS is different from the one used for OMI and SCIAMACHY.

P9185, l. 3, l. 6: Quantify low and larger

We will clarify as follows:

“SBUV-2 on NOAA 18 showed increasing negative biases from 4 to 8 DU at between 74° and 82°S.”

P9187, l. 13: How does 1 ppbv underestimation of stratospheric humidity compare with estimated errors of MLS humidity?

MLS errors for water vapor varies from 15% at 100hPa to 4% at 1 hPa. (http://mls.jpl.nasa.gov/products/h2o_product.php) It is smaller than the identified error in humidity. See the re-formulation in the response to reviewer #2.

P9187, l. 25: Is 5% expected from missing upper part of the column based on climatology?

The 5% has been calculated by assuming that the last (i.e. at the highest altitude) measured sonde concentration is the concentration in the levels above the highest recorded altitude.

P9187, l. 27: Quantify good correlation.

We will include the values of the correlation coefficients in the text as follows:

"Although there was a correlation of 0.85, 0.87 and 0.91 between the observations and the FC runs by IFS-MOZART, IFS-TM5 and IFS respectively, IFS-MOZART and IFS-TM5 mostly over-predicted whereas IFS under-predicted the observations."

P9189, l. 12: Does this scheme produce ozone loss in the dark?

The linear scheme does not produce ozone loss in the dark as consequence of term accounting for the heterogeneous chemistry.
P9190, l. 4: Suggest replacing "ozone hole" by "extent of the ozone loss".

We will follow this suggestion.

P9190, l. 11: Quantify "maintaining the positive impact".

As pointed out in the response to reviewer # 2, we will extent the section on the predictability by showing the change in bias of the FC15 runs and a passive tracer separately for the period of the ozone hole development and closure.

P9195, l. 10: How do weights given to observations differ from Greer's? What observation and forecast errors are used here vs. Greer et al or Coy et al 2007?

Coy et al. 2007 report SD of observations but not the SD of the observations error. Geer et al. 2006 use an error for MIPAS of about 5% in the range between 50 and 1 hPa, but the error reaches 90% at 300 hPa. The MIPAS errors are of a similar size as the applied errors of MLS. We will add the following:

"The applied observation errors for MIPAS were of similar size (5%) as the values used for MLS in this study."

P9195, l. 24: Add Stajner and Wargan (2004).

We will add the reference

<u>New references:</u>

Rind, D., Lerner, J., Jonas, J., and McLinden, C.: Effects of resolution and model physics on tracer transports in the NASA Goddard Institute for Space Studies general circulation models, J. Geophys. Res., 112, D09315, doi:10.1029/2006JD007476, 2007.

Coy, L., D. R. Allen, S. D. Eckermann, J. P. McCormack, I. Stajner, T. F. Hogan (2007), Effects of model chemistry and data biases on stratospheric ozone assimilation, Atmos. Chem. Phys., 7, 2917–2935, 2007.

Gray, L. J. and Pyle, J. A.: A two dimensional model of the quasi-biennial oscillation of ozone, J. Atmos. Sci., 46, 203–220, 1989.

Stajner, I., and Wargan, K.: Antarctic stratospheric ozone from the assimilation of occultation data, Geophys. Res. Lett, 31, L18108, doi:10.1029/2004GL020846, 2004.

Stajner, I., Wargan, K. , Chang, L.-P., Hayashi, H. , Pawson, S. and Nakajima, H. : Assimilation of ozone profiles from the Improved Limb Atmospheric Spectrometer-II: study of Antarctic ozone, J. Geophys. Res., 111, D11S14, doi:10.1029, 2006.