

## ***Interactive comment on “Middle atmospheric ozone, nitrogen dioxide, and nitrogen trioxide in 2002–2011: SD-WACCM simulations compared to GOMOS observations” by Erkki Kyrölä et al.***

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Received and published: 14 March 2018

We want to thank Reviewer 2 for his/her elaborate review of the paper. The answers to individual comments are shown below.

In addition to changes demanded by the reviewers we have updated all figures in order to increase their information content. In Figs. 5-7, 11-12, we have shown only 2 altitudes (earlier 3) for clarity. We have removed Fig. 14 because its content overlaps with Fig. 13. For Fig. 13 we have added also the WACCM-GOMOS difference plot. Figure 20 is redrawn. Instead showing the NO<sub>3</sub>/O<sub>3</sub> ratio from theory, WACCM and GOMOS, we show the relative differences of this ratio from theory and WACCM to the ratio from

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GOMOS. For readers' delight we have added one new figure (Fig. 21) that shows the vertical column differences between WACCM and GOMOS for our three gases.

We have changed our interpretation of the WACCM-GOMOS difference in the Arctic in the lower stratosphere. We assumed earlier that it could be a consequence of the NO<sub>2</sub> increases from protons and downdrafts. Now the more plausible reason is that GOMOS sees larger ozone destruction during the Arctic winter than what WACCM simulates. This can be seen in new Figs. 6-7.

Specific answers to comments:

Figures 1, 8, and 15 really should have a third panel that shows all the relative difference profiles (especially 8 and 15). Answer: These figures are now updated.

P1 Throughout the abstract, many value judgements are made (e.g. reasonable agreement, high correlation, etc.) without quantifying the values. Please backup these claims with the exact values that you have measured. Answer: Abstract changed.

Line 15 – unclear what is meant by “the validity region” Answer: Validity region in altitude. Text changed.

P2 Lines 5-6 – please briefly explain how these references are examples of improving understanding of accuracy. Answer: text changed.

Line 14 – Smith et al. 2013 (doi:10.1002/jgrd.50445) would be an excellent ref to include as well. Answer: Added.

Lines 14-16 – Mention of validation and comparison studies should include references. Answer: Reference to Hubert et al. (2016) added.

Line 22 – “see” on its own tends to imply a full list, something like “e.g.” or “see for example” would be more appropriate Answer: Text changed.

Line 24 – should mention this is at all altitudes. Answer: Text changed.

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Line 26 – change to “to the lower thermosphere” Answer: Text changed.

Line 32 – Does this mean that ion chemistry is included? Or just (non ion) chemistry within the D region? Please specify in the text. Answer: Yes, text changed.

P3 Lines 1-5 – tends to be vague. Terms “reasonable agreement,” “compares well,” and “found to be similar” need specific quantified values in order to back up these judgments. Same with “good” on line 11. Answer: We have now added WACCM total ozone bias numbers from Eyring, V., Shepherd, T. G., and W., W. D., eds.: SPARC CCMVal Report on the Evaluation of Chemistry-Climate Models, vol. No. 5. We removed the statement about WACCM and HALOE, because we could not find any numbers or even deviation plots from literature, only messy plots with thousand or more models included!

Line 11 – What is meant by brightest? Answer: Measured by the apparent magnitude at Earth’s position.

Line 16 – “mesosphere and” can be deleted Answer: Text changed.

Line 17 – “comparison” should be “comparisons” Answer: Text changed.

Line 27 – “Sec. the” should be “Sec. 3 the” Answer: Text changed.

P4 Lines 1-2 – should be “this approach has” Answer: Text changed.

Line 6 – “in detail” is not needed Answer: Text changed.

Line 7 – “those” is not necessary Answer: Text changed.

Line 12 – should be something more like “there is an ozone-specific flag that screens out stars. . .” Answer: Text changed.

Line 14 – should be “outliers” and “stratosphere” Answer: Text hanged.

Lines 14-15 – I assume you’re not setting the flags to zero, rather you’re only using profiles where flag values are zero. Answer: Text changed.

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Line 27 – do you mean “within  $\pm 3\%$ ” ? Answer: Text changed.

Line 30 – do you mean “within  $\pm 4\%$ ” ? Answer: Text changed.

P5 5th line (labelled l38) – could reiterate that this is nighttime profiles being compared. Answer: Text changed.

Line 9 – Sheese et al. 2016 (doi:10.5194/amt-9-5781-2016) is the more recent ACE-FTS NO<sub>y</sub> validation reference and should be added. Seems to show GOMOS  $\hat{\Delta}$  0-10% higher between 23-30 km,  $\hat{\Delta}$  25% higher at 30-45 km (although seems ACE-FTS has low bias of  $\hat{\Delta}$  10% in this region). Answer: Text updated.

Line 25 – what kind of observations? Answer: Historical surface concentrations of greenhouse gases were taken from Meinshausen et al. (2011)”. Meinshausen, M., and Coauthors, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109, 213–241, doi:10.1007/s10584-011-0156-z. This reference added and text changed.

P6 Line 16 – delete “a” Answer: Text changed.

Line 19 – would be good to add here how many collocated profiles there are Answer: Text changed

P7 Eqn 2 – could change to “100%” Answer: Changed

Line 6 – “WACCM” should be “GOMOS” Answer: Yes, text changed

Line 10 – “. . . processes while keeping reasonable. . .” Line 11 – is it the Pearson correlation coefficient? Answer: Yes, it is Pearson. Text changed.

Line 12 – What is meant by “averages over number of”? Answer: Text hanged.

Lines 13-14 – The equation doesn’t make it clear exactly how the data is being filtered. A please rephrase for clarity. Is this method done using all data at a given altitude? Is it done in latitude bins? Also, in atmospheric datasets where the data is very often

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neither Gaussian nor uni-modal, using the MAD as a filter can often lead to filtering out a lot of inlying data with the outlying data. If you haven't already, please check that this method isn't "over-filtering" your data, and if everything is okay it would be good to specify that this check was done and how much data is filtered out using this method. Answer: This part is reorganised and partly rewritten. For ozone the outlier filter removes on average 1 % of measurements. At the ozone minimum altitude and in the polar regions the filtering effect is larger, up to 5 %. For NO<sub>2</sub> and NO<sub>3</sub> the filtering is from 1% (non-polar) to 5% (polar regions). We consider these numbers acceptable. Anyhow, in this paper our focus is on differences of paired data between GOMOS and WACCM, not so much 100% mapping of the atmosphere with all its diversity. The sparse sampling of GOMOS measurements does not support this kind of dream.

P8 Figure 1 – It would be nice if both figures had the same y-axis labels Answer: Changed. We removed the km-axis as we added the third sub-panel requested by the reviewer. Available space disappeared.

Caption – Please specify in caption that these are Aug-Sept profiles Answer: Text hanged.

Discussion of Figure 1 – It would be worth noting that both GOMOS and WACCM are exhibiting the tertiary peak and are in good agreement in both height (68 km, which actually seems a bit low for the tertiary peak, see Degenstein et al 2005, doi:10.1016/j.jastp.2005.06.019) and concentration. Answer: Some discussion of the tertiary peaks is done after Fig.3. and the reference added. In this kind of mission average the tertiary peak is not so clearly visible and in our mind it does not deserve detailed discussion.

Line 13 – delete "the" Answer: Changed.

P9 Line 1 – "reaches again 2%" must be a typo. At the secondary peak, the differences clearly much larger. Answer: No, it is correct. If we use the words from the mean-world we are saying here that the error of the mean averaged over the 10 year mission is 2%.

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The standard deviation during each year is of course much larger but the mean is quite precise.

Fig 2 caption – might want to say "A cell with a dot marks where there are no collocated profiles." Same with Figures 3, 4, 9, 10, 16, and 17. Answer: Text changed. But should it be like "A cell with a dot marks a point where there are no collocated profiles"?

P10 Line 18 – "in the two cases" Answer. Text changed.

Line 30 – it may be more prudent to something more along the lines of "we have not been able to identify any potential sources of uncertainty that could lead to such a large error in the GOMOS data" Answer: Text changed.

P11 Figure 5 – At the secondary maximum the WACCM seasonal variation is very difficult to discern and it's not immediately clear that WACCM and GOMOS are in phase. Could this panel have the y-axis on a log scale? Answer: Changed. And we have reduced the displayed altitudes from 3 to 2 in order to improve the clarity of the figure.

P12 Figures 6 – A legend (maybe on the rhs) would make the plots much easier to read. Same with Figures 7, 11, 12, 18. Answer: Legends added.

Figure 7 – The red and blue is slightly confusing, because the reader will naturally be comparing to Figure 6 where the same colours indicate only Arctic values. Please use two styles of lines that relate better to Figure 6. Same with Figure 12. Answer: We have added legends, it probably helps. In many figures we are suffering from the availability of clearly differing colours. The only help for a reader is to enlarge plots on the computer screen!

Line 34 – "correlation is typically very high," Answer: The changed.

Lines 34-35 – I find this sentence somewhat confusing, please rephrase for better clarity. Answer: Text changed slightly.

P13 First paragraph – please include quantification of the differences and correlation

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for all three panels of Figure 5. Answer: Text changed.

Line 4 (6th line) – “whereas” Answer: Text changed.

Lines 5-12 – Please include quantification of the differences and correlation for all three panels of Figure 6 and 7. Answer: Text changed.

Figure 8 – should include altitude scale to match Fig 1. Same with Figure 15. Answer: Because we added third panel, we had to remove all the km-scales.

P14 First paragraph – are these also Aug-Sept? If so, please mention here and in Fig 8 caption. Same with NO<sub>3</sub> results/figure. Answer: Text changed.

Fourth line – “maximum at 5 hPa the difference is within” Answer: Text changed.

Line 9 – “will be discussed” Answer: Text changed.

Line 11 – “is typically 0-10%” and “typically agree within  $\pm 5\%$ ” as differences do reach higher values in the respective regions Answer: Text changed.

P15 First paragraph – Please quantify discussion of correlation coefficients Answer: Text changed.

Line 13 – Should start sentence with something like, “As seen in Fig. 13 and 14, . . .” Answer: Text changed.

P16 First line – it’s somewhat confusing that you’re discussing the difference in ppb when figure 13 is in %, please make this consistent (or discuss both % and ppb). Unless, you’re referring to Fig 14 here, but Fig 14 doesn’t show results for 0.5 hPa. Either way, this section needs to be made clearer (as to what Figures you’re discussing and what they show). Answer: In Fig. 13 we now show both GOMOS and WACCM, and mixing ratio absolute difference. Fig. 14 is now removed. Text updated.

Line 5 – “peak density,  $\hat{\alpha}_{ij}2hPa$ ” Answer: Text changed.

Line 10 – “is typically inside” Answer: Text changed.

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P17 Figure 13 – units are missing on both panels Answer: Added.

Last line – “The secret behind” could be something more like “the reason for” Answer: Text changed.

P18 Fifth line – delete “to state”. Also is there a reference for MERRA underestimating temperatures in these regions? If not, please explain why it is plausible (i.e. SSWs). Answer: We have mellowed the text.

P20 Figure 18 – middle panel colours are not explained (should they be blue and red?). Would also suggest using different colours for the bottom panel Answer: Changed. We have added line legends.

Line 7 – Do you mean to say that MERRA temperature overestimates are a result WACCM overestimates of NO<sub>3</sub>? Instead of “consequently” do you mean “likewise”? Answer: We mean that MERRA temperature overestimates are the probable source of WACCM NO<sub>3</sub> overestimates. Text improved.

Line 10 – “mixing ratio values” Answer: Text changed.

Line 12 – The sentence, “The very high. . . exponential function.” Needs more discussion with quantification. Answer: We removed this sentence because there are not enough cases where this statement is true.

Figure 20 – I believe that left and right panels are switched (or incorrectly referenced in the caption). Also, I appreciate that all three panels have been plotted on the same scale, but this makes them more difficult to interpret. I recommend having the y-axes on different scales. I would also highly recommend having the y-axes on a log scale. This would again make the figures and the discussion thereof clearer. Answer: Yes, yes, the caption is wrong! Thanks for your keen eye. We have now plotted using log-scale. The plots are now much more interesting. Because of the re-plotting, we discovered a bug in our software that caused corruption in the temperature data. All figures including temperature data are now corrected. Hopefully everything is now correct in Fig. 20!

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P21 First line – delete “ref.” Answer: Text changed.

P22 It is unclear here what the point of comparing the GOMOS and WACCM NO<sub>3</sub>/O<sub>3</sub> ratio to theoretical calculations is. What does this tell us? Answer: Our approach is this: A complicated model like WACCM is entirely a numerical machine with massive amounts of approximations and parametrisations. If there are results from chemical and physical theories that numerical models should fulfil, we need to check if they do. Because these kind of check point results are not necessarily universally true, but assume some additional conditions (in our case chemical equilibrium), it is important also to see if they are obeyed by experimental measurements.

Line 5 – “comparison is done” should be “comparisons are done” Answer: Text changed.

P23 Line 7 – “mesosphere below” should be “mesosphere just below” Answer: Text changed.

Line 16 – what is meant by “to large extent”? When can and can’t it be fitted to exponential function? Answer: Changed to “fitted reasonably well”.

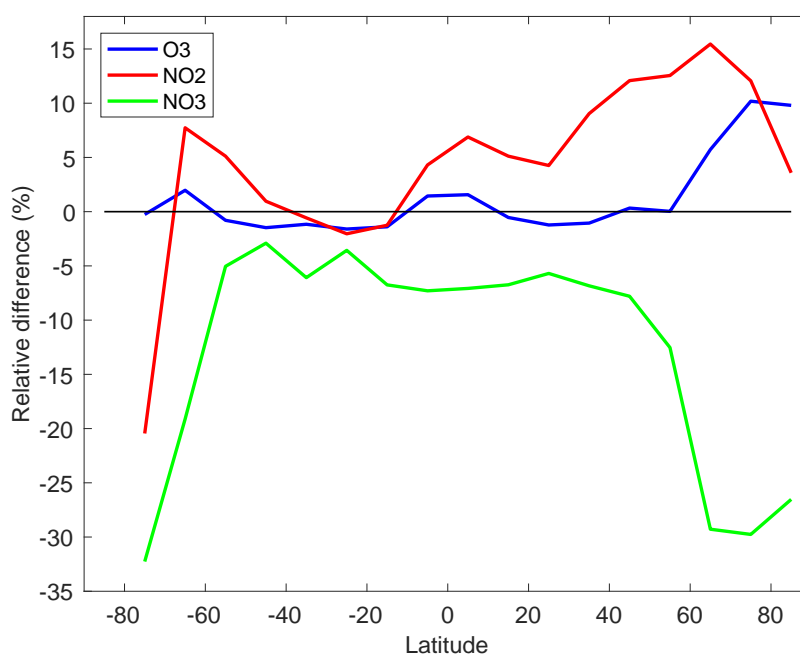
Lines 18-19 – I disagree that you’ve shown that you can use NO<sub>3</sub> measurements as a proxy for SSWs. How did you show this? This would need more analysis and much more discussion. You would need to start by showing that deviations from the exponential curve only occur during SSWs. Answer: You are correct. Because this topic is not in the focal point of the paper we leave further analysis to future publications. We have downshifted our text.

Lines 21-22 – “physics and chemistry.” should be “physics and chemistry is necessary.” Answer: Text changed.

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Interactive comment on Atmos. Chem. Phys. Discuss., <https://doi.org/10.5194/acp-2017-1161>, 2017.

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**Fig. 1.** The The relative difference of WACCM and GOMOS vertical columns of ozone, NO<sub>2</sub> and \NO<sub>3</sub>.

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