

AUTHORS' RESPONSE TO THE REFEREE 1 COMMENTS

We thank Referee 1 for helpful comments regarding improving our manuscript. Below are point by point replies to the particular issues raised.

This paper deals with the recovery of Arctic ozone in a future climate under increasing greenhouse gas concentrations and declining inorganic chlorine. In contrast to earlier studies the authors use an ensemble mean of seven transient simulations to capture the interannual variability in Arctic ozone. The special focus is on the possibility of individual years with strong ozone depletion even after 2060 when halogen loading has become relatively low. I find the paper appropriate for publication in ACP after my minor suggestions have been considered and my questions have been clarified.

General comments:

- The authors need to be very careful with the references in the text pointing to the single figures. There are some mistakes which can confuse the reader.*
- It need to be clearly stated that the years '2060' and '2063' are model years coming out of a not nudged simulation and are therefore relatively arbitrary. In some parts it sounds as if we get a really strong ozone loss in the future year 2063 and a really weak one in 2060. This needs to be clarified.*
- The authors have included a lot of citations in their manuscript and compare their results with many of these studies. In some cases they need to be more specified. In my opinion some studies do not exactly show what is stated here.*
- There are a lot of typos in the references. A cross check should be done before final publication.*

These points are addressed below.

Specific comments:

- Page 4, line 27: How are orographic and non-orographic gravity waves parameterized? Please provide a reference.*

We have added this information to the manuscript.

- Page 5, lines 15 - 17: I don't really understand why these six year bins are excluded. The supplement only shows which years are affected. Please provide some more information on this, here or in the supplement.*

For these periods there was an error when the model was run and we do not have sensible data.

- Page 6, line 11: 'In all six reactions, a net loss of 2 odd oxygen molecules occurs per cycle.' → Do you mean 2 molecules ozone? But in cycle 3 there is only one. Please clarify this.*

We have clarified this in the manuscript.

Each cycle leads to net loss of 2 odd oxygen molecules ($O_x=O_3+O(^3P)+O(^1D)$). As discussed in Lee et al. (2002), the concentrations of ozone are significantly larger than of atomic oxygen, in particular in the polar lower stratosphere in winter/spring (which is the region studied here), therefore, we assume that $[O_x] \approx [O_3]$ and, thus, $d[O_x]/dt \approx d[O_3]/dt$.

□ *Page 6, line 24: 'averaged from 65°N to the pole.' → Why do you use exactly 65°N 90°N? Have you also tested other latitudes, for example 60°N - 90°N and does this change the results?*

The 65-90°N average was chosen as a compromise between capturing a proportionally large fraction of the polar vortex while minimising the proportion of the extra vortex region, and including the edges of the vortex where in early winter halogen activation will take place preferentially (as there is little sunlight at higher latitudes).

□ *Page 7, line 6: see comment above*

As above.

□ *Page 10, lines 17 - 19: '...in agreement with Langematz et al. (2014).' → This statement should be specified. Do you compare with Figure 2a from Langematz et al. (2014)? From this figure I see a significant trend at 100 hPa, which is not the same as in your study. Moreover, you have to note that the time ranges are not identical.*

We have changed the text. ("In comparison, Langematz et al. (2014) found a statistically significant cooling trend in early winter over 1960-2100 throughout the polar stratosphere.")

□ *Page 11, line 26: 'This is in broad agreement with the findings in Langematz et al. (2014).' → Where do you get this from? The focus in their study is on the vortex duration and not on the zonal wind trend. You need to be more specific with your comment.*

We have changed the text ("Langematz et al. (2014) analysed the timing of the formation of the NH polar vortex and found a statistically significant trend towards earlier vortex formation. It is possible that the strengthening of the stratospheric zonal wind in autumn/early winter in our ensembles could be related to a similar effect. ").

□ *Page 12, line 3: Maybe you can call Section 3.3 'Case studies of exceptionally low and high ozone events' as you show results from both - low and high - and not only from low ozone events. This should be changed also in the Introduction (page 4, lines 5 - 7).*

We have changed the text to "Case study of exceptionally low and average ozone events".

□ *Page 12, Section 3.3.: As you use free running, and no nudged model simulations, you won't expect that your 'model' years resemble 'real' years. Please make sure that the 'years' 2060 and 2063 are 'model' years. Do you really need this numbers? Maybe you can skip them and refer to low and high ozone events.*

We have added an explanatory sentence, and we also now refer to 'model years'.

□ *Be very careful with the references on the figures:*

- *Page 12, lines 25 - 26: ... (see Fig. 7(b) and 8 (b)).*
- *Page 12, line 30: (Fig. 8(b)) and not 8(a)!!!*
- *Page 12, line 31: (Fig. 8(b)) and not 8(a)!!!*
- *Page 13, line 1: (Fig. 8(b)) and not 8(a)!!!*
- *Page 13, line 26: (Fig. 9(c)) and not 9(b)!!!*

Thank you for spotting this, we have corrected the text.

- *Page 15, line 31: '...account for ~20%...' → This is a very crude estimate. Please be more specific.*

We believe that this level of accuracy is adequate. Given the limitations of the diagnostics used, it is more appropriate to give an order of magnitude estimate than a precise (but not necessarily accurate) number.

Technical corrections:

- *Page 2, lines 9 - 10: reference for 'Montreal Protocol on Substances that Deplete the Ozone Layer'*

We have clarified that this is an international treaty.

- *Page 3, line 19: ... volume of PSCs (VPSC) → the abbreviation 'PSCs' has been introduced in line 9*

We have corrected the text.

- *Page 4, line 1: Stratosphere -troposphere Processes And their Role in Climate (SPARC)*

We have corrected the text.

- *Page 4, line 2: Please provide a reference for CCMI.*

We have added the requested reference.

- *Page 4, line 16: ... the recent SPARC Report on the Lifetimes of ... (SPARC, 2013;...) → Be careful that this is in line with the citation on page 21, line 14f.*

We have corrected the text.

- *Page 4, line 24: The dot at the end of the sentence is missing.*

We have corrected the text.

- *Page 5, line 13: You may introduce an abbreviation for 'sea-ice concentrations' here and use it on page 8, lines 18 and 27.*

We have added the abbreviation.

- *Page 5, line 17: ...long periods are excluded...*

It is the 'total' that 'is' excluded.

□ *Page 5, line 23: ... and a more minor ClO + O(3P) cycle... → You should include (Cycle 3, reference) as before.*

We have added this.

□ *Page 11, lines 3 - 4: The references should be sorted by year.*

We have corrected the text.

□ *Page 11, lines 29 - 30: ...(see also Langematz et al., 2014).*

We have corrected the text.

□ *Page 12, line 12: ... higher than in model year 2063.*

We have corrected the text.

□ *Page 12, line 15: use the abbreviation 'BDC', as introduced before*

We have corrected the text.

□ *Page 13, line 17: ... ClO concentrations in 2063 compared to 2060 (Fig. 9(c)). → The figure shows a difference and not the concentrations in 2063.*

We have corrected the text. Also, we have added a figure showing the evolution of ClO at 21.5 km in the two case study years to the supplement.

□ *Page 15, line 26: ... 'exemplified by a case study in 2063.' → Either you include 'model year' here, or you skip the year. In the Conclusions I would prefer to skip the years and use 'low and high ozone events instead.*

As suggested, we no longer use “2063” and “2060” in Sect. 4 (i.e. Conclusions).

□ *Page 15, line 32: '...in year 2063 and a year from the same period ... ' → Better: '...between this year and a year from the same period ...'*

Changed to “between this low ozone year and a year from the same period with near average springtime ozone”

□ *Page 17, line 4: ... Steil, B.; and Tian, W....*

We have corrected the text.

Page 17, line 5: The dot is missing at the end of the reference.

We have corrected the text.

Page 17, line 19: Drdla, K., and Müller, R.:...

We have corrected the text.

Page 19, line 10: ...Oberländer, S., ...

We have corrected the text.

Page 21, line 30: Tilmes, S., Müller, R., ...

We have corrected the text.

Page 22, line 5: ... and Müller, R.: ...

We have corrected the text.

Page 24, line 4: ... 11-year running average, respectively.

We have corrected the text.

Page 24, line 5: ... 2060 and 2063, respectively, described in Sect. 3.3.

We have corrected the text.

Page 27, line 2: ... 11-year running average, respectively.

We have corrected the text.

Page 27, line 6: 'As in Figure 4, ...' → I would prefer an independent figure caption for Figure 6, as the only agreements with Figure 4 are the pressure levels and the meaning of the points and bars.

We have added an independent caption for former Fig. 6 (now Fig. 7).

REFERENCES

Langematz, U., Meul, S., Grunow, K., Romanowsky, E., Oberländer, S., Abalichin, J., and Kubin, A.: Future Arctic temperature and ozone: The role of stratospheric composition changes, *J. Geophys. Res.-Atmos.*, 119, 2092-2112, doi:10.1002/2013jd021100, 2014.

Lee, A. M., Jones, R. L., Kilbane-Dawe, I., and Pyle, J. A.: Diagnosing ozone loss in the extratropical lower stratosphere, *J. Geophys. Res.-Atmos.*, 107, NO. D11, 4110, doi:10.1029/2001jd000538, 2002.