Reply to reviews: Weakening of springtime Arctic ozone depletion with climate change

Marina Friedel, Gabriel Chiodo, Timofei Sukhodolov, James Keeble, Thomas Peter, Svenja Seeber, Andrea Stenke, Hideharu Akiyoshi, Eugene Rozanov, David Plummer, Patrick Jöckel, Guang Zeng, Olaf Morgenstern, Béatrice Josse

RC = Reviewer Comment

AR = Author Reply

Reviewer 2

We thank the reviewer for their detailed assessment of our manuscript and helpful comments. Please find the point-by-point response below.

RC 2.1

Friedel et al. provide a comprehensive study on the future evolution of ozone minima over the Arctic polar cap. The authors present a thorough analysis of a series of transient and timeslice simulations with 2 CCMs (WACCM and SOCOL) as well as the cohort of simulations available from CCMI1 and CCMI-2022 models. In their study the authors: i) address individual model weaknesses (warm and cold biases) related to the realization of ozone minima; ii) explore the related spread in modelled springtime ozone anomalies at present and for different future climate scenarios; iii) quantify the magnitude of ozone anomalies for early and late 21st century and temporal changes in these anomalies; iv) illustrate how the amount of ClOx available in CCMs drives ozone minima at present and also determines their future trends; and v) detail how inter-model spread can be used to constrain ozone minima projections.

The manuscript is timely and well prepared. The study sheds new light on the long-standing question regarding the future evolution of Arctic low ozone extremes and emphasizes the central role of declining ODS abundances for future Arctic ozone, both mean and extreme, across potential climate pathways.

I recommend accepting this manuscript for publication after addressing the comments provided below.

General comments:

Section 3.1, L163-170: The authors examine ozone minima present and future, and the model spread in ozone minima across CCMs. While the text and Fig. 2 illustrate well the overall change in ozone anomalies I would suggest also including a short text passage or supplemental table detailing the timing of the most pronounced ozone minima per CCM and scenario (on decadal basis).

AR 2.1

It is not entirely clear to us what the reviewer is suggesting. Is the seasonal timing of the ozone minima in each spring meant, or rather the timing of the e.g. 5 most pronounced ozone minima in each CCM over the 21^{st} century? If it is the former, we are afraid that the calculation of the date of the ozone minima within each season would require data on daily resolution, which is only available for a fraction (ca. 50%) of the models. If the latter is meant, we are unsure what the benefit of such additional information would be. We would therefore like to ask the reviewer to please specify what they mean with "timing of the most pronounced ozone minima" and what the benefit of showing it would be.

RC 2.2

Section 3.3, L210-228: I would assume the picture would not change strongly but how would Fig. 3 look like if you restrict to ClOx and temperature in spring (March-April)?

AR 2.2

Thank you for this comment. Figure R2 shows the connection between springtime Arctic ozone minima and ClOx/temperature at 50 hPa when only values in March-April are being considered. As one can see, the correlations are still moderate to strong, but weaker than when considering January-April means for ClOx and temperature as in Fig. 3. We believe that when averaging over March-April, a large fraction of the averaging window might be after the chemical ozone depletion (depending on the model). In SOCOL and WACCM, for which we conducted extensive analyses on the seasonal timing of ozone minima, we found that ozone minima typically occur between mid-March and mid-April in these models (Friedel et al., 2022a, b). ClOx and temperature anomalies happening after the ozone minima are no good proxies for the amount of ozone depleted. Rather, one should consider temperature and ClOx anomalies anticipating the ozone minima. In fact, using January-February means for ClOx and temperature yields correlations of -0.80 and -0.69, respectively, which is the same as in Fig. 3 in the paper (where Jan-Apr mean values where chosen for ClOx and temperature).

RC 2.3

Section 3.3, L261-264: I would call the correlation between stratospheric temperature trends and ozone minima of 0.59 moderate not weak. However, I agree with the dominance of some models for overall R. Thus, I would recommend specifying how R changes if the two most extreme (positive and negative) models are removed.

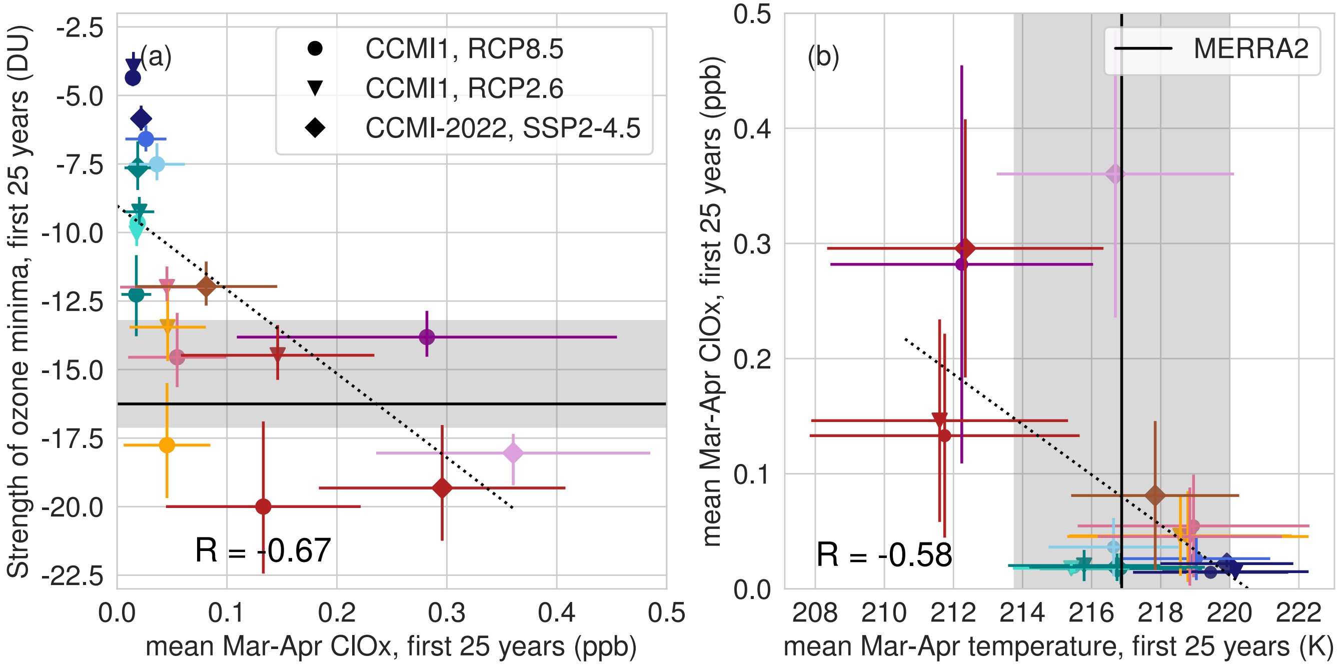

Figure R1. Same as Fig. 3 in the manuscript, but for March-April averages for ClOx and temperature.

AR 2.3

The wording has been changed to "moderate". When calculating the correlation coefficient excluding the two most extreme positive and negative values, R reduces to 0.5.

RC 2.4

Section A2: I agree with the authors to apply model weighting, however given the substantial difference in weight for different models across scenarios I would suggest adding a second panel to Fig. A5 showing also the evolution of the unweighted multi-model mean of ozone minima strength.

AR 2.4

Thank you for this suggestion. We included the unweighted multi-model mean as stippled lines in Fig. A5.

RC 2.5

Technical comments:

L 155: on a multimodel mean → on the multimodel mean

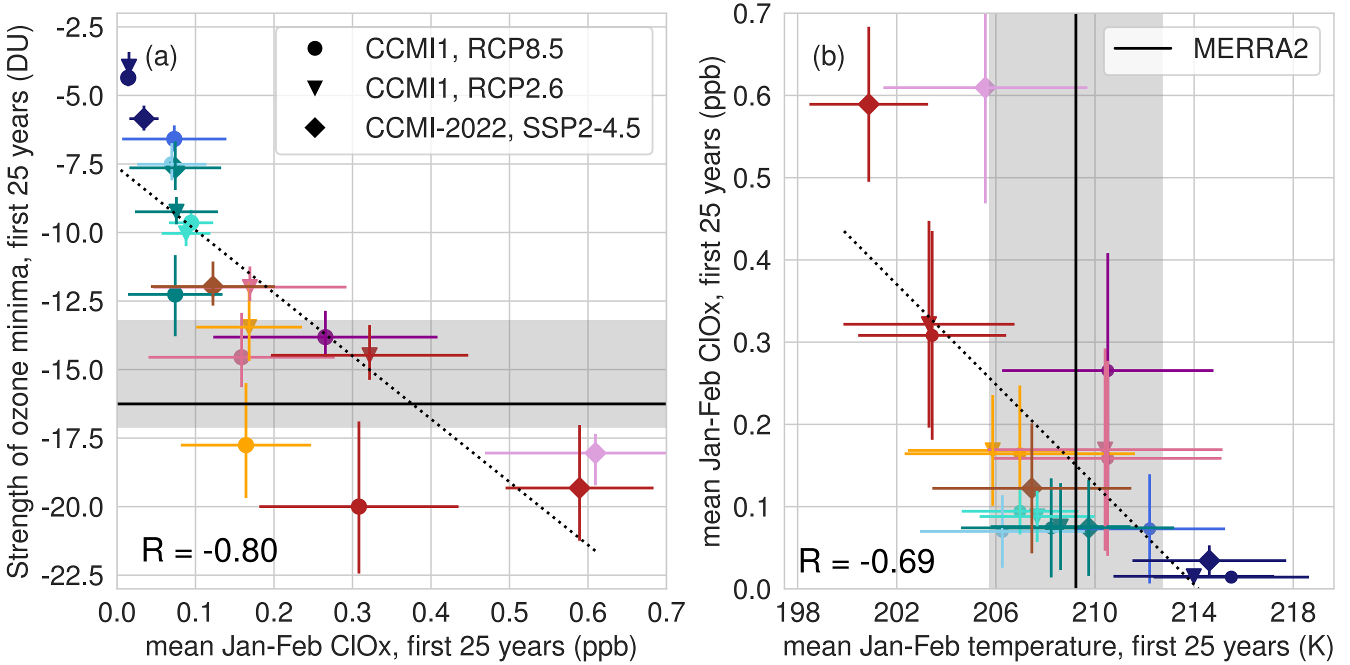

Figure R2. Same as Fig. 3 in the manuscript, but for January-February averages for ClOx and temperature.

AR 2.5

This has been adapted.

RC 2.6

L166: Development → evolution (also in caption of Fig. 2)

AR 2.6

This has been adapted.

RC 2.7

L210: reduction of the BDC → weakening of the BDC

AR 2.7

This has been adapted.

RC 2.8

L273: Fig.5 → Fig. 5

AR 2.8

This has been corrected.

RC 2.9

Figure 1, caption: normalized by mean ozone → normalized by mean partial column ozone

AR 2.9

This has been adapted.

RC 2.10

Fig. 2, caption: normalized by ozone climatology → normalized by the ozone climatology

AR 2.10

This has been adapted.

RC 2.11

Fig. A7: is the vertical whisker for CMAM ClOx missing?

AR 2.11

Thank you for this comment. The whisker is actually too small to be seen on this plot (the standard deviation for January-April ClOx in CMAM is 0.004 ppmv). Figure R3 shows the Jan-Apr mean ClOx development over the 21^{st} century in the lower stratosphere (50 hPa). The dark blue line shows CMAM. It can be seen that CMAM has (i) very little ClOx in the first place, and (ii) the interannual ClOx variability in this model is extremely small. Hence, the uncertainty in this variable for this model is small.

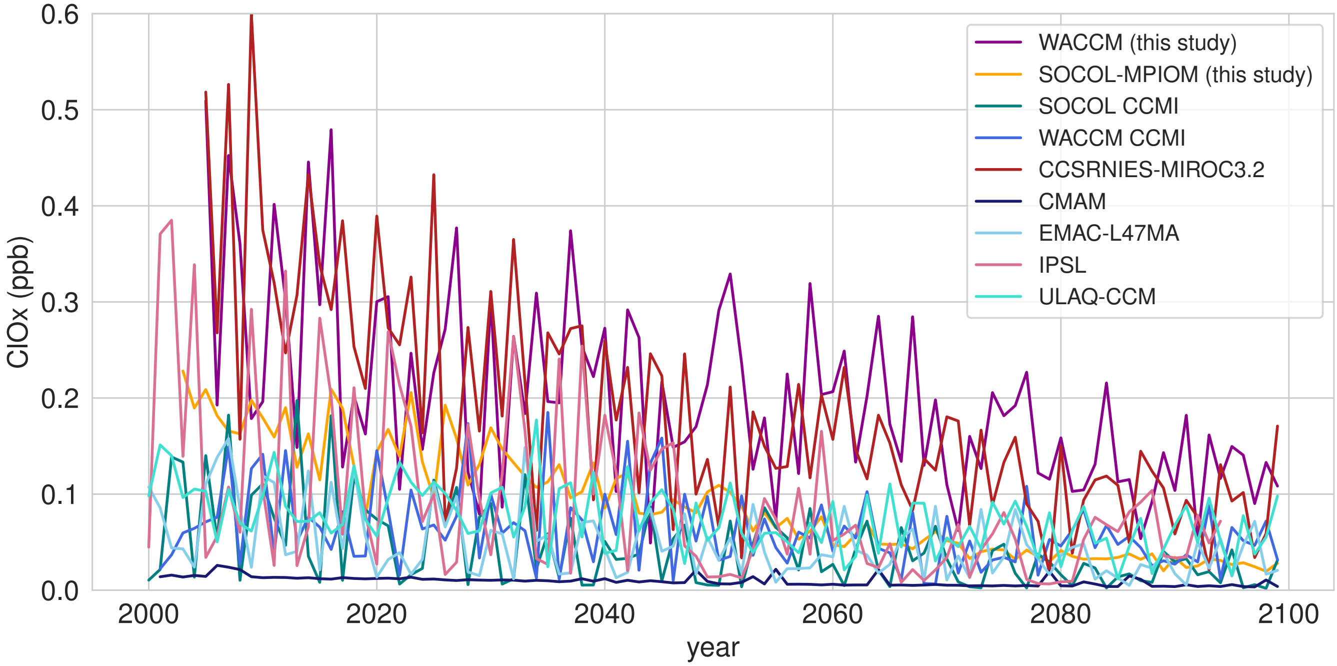

Figure R3. Ensemble mean ClOx develoment (Jan-Apr) at 50 hPa over the 21st century.

References

Friedel, M., Chiodo, G., Stenke, A., Domeisen, D. I., Fueglistaler, S., Anet, J., and Peter, T.: Springtime Arctic ozone depletion forces Northern Hemisphere climate anomalies, Nature Geoscience, 15, 541–547, https://doi.org/https://doi.org/10.1038/s41561-022-00974-7, 2022a.

Friedel, M., Chiodo, G., Stenke, A., Domeisen, D. I. V., and Peter, T.: Effects of Arctic ozone on the stratospheric spring onset and its surface impact, Atmospheric Chemistry and Physics, 22, 13 997–14 017, https://doi.org/10.5194/acp-22-13997-2022, 2022b.