Reply to reviews: Effects of Arctic ozone on the stratospheric spring onset and its surface impact

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September 27, 2022

RC = Reviewer Comment
AR = Author Reply

Reviewer 1

RC 1.1 Overall, Friedel et al. present a comprehensive analysis of the influence of interactive ozone on final stratospheric warmings, a nice follow-on from a complementary paper (Friedel et al. 2022) from some of the same co-authors. Here the authors demonstrate a clear role for ozone coupling in the FSW timing, surface signatures (for high ozone cases) and the vertical evolution of the FSW. The paper is clearly written and the authors perform careful analysis to support their hypotheses. I only have a few points of clarification that I would like to see addressed before publication:

Minor Comments/Clarifications:

1. FSW threshold of 7 m/s in lower stratosphere: Can the authors elaborate on why this particular threshold was chosen? Is this a recommendation based on the cited articles to achieve FSWs each year or does this threshold specifically apply to WACCM and SOCOL? It seems that a different threshold might be appropriate for each individual model. I am curious about this in terms of the surface impacts, in particular. For the low ozone cases, are the surface impacts (SLP and TAS anomalies) sensitive to the chosen threshold?

AR 1.1 Thank you for this comment. Both models, SOCOL and WACCM, have a cold polar vortex bias, which is especially pronounced in SOCOL (see Fig. A1 b) with years where the stratospheric winds in the lower stratosphere stay westerly throughout the year. The chosen threshold of 7 m/s is the lowest possible threshold so that this model produces a FSW every single year. This was tested for steps of 1 m/s. For WACCM and MERRA2, a lower threshold (i.e. a threshold closer to zero) could be used in principle. However, the question remains as to how a model-specific threshold should be defined (e.g. based on the climatological vortex strength, the lowest possible threshold for each model, ...). To this end, we performed sensitivity tests with WACCM in order to investigate the sensitivity of the surface signal following the FSWs in high (Fig. R1) and low (Fig. R2) ozone springs to different thresholds: 10 m/s, 5 m/s and 3 m/s. Results show that the magnitude of the sea level pressure (SLP) and surface temperature anomalies following FSWs depends slightly on the selected threshold, with lower thresholds showing a smaller surface signal. However, the pattern of the surface signal, and especially the differences between experiments with (INT-3D) and without (CLIM-3D) interactive ozone chemistry, show no sensitivity to the chosen threshold. This lends confidence to the methodology chosen here (with a threshold of 7 m/s defining the onset of FSWs at 50 hPa) and we see no need for a model-specific threshold. A short statement on this has now been added to the methods section following line 132.

RC 1.2 2. Definition of ozone max/min: Based on the definition of your ozone max/min, is it possible to get overlapping years? Based on Fig. A2, the SOCOL ozone has a very clear double peak for the low ozone cases. In addition, the SOCOL low ozone seasonal cycle seems to have an unusual shape with an extreme minimum in March and then a large recovery - makes me wonder a bit about this 5-day running mean approach. Maybe this is too short a time period over which to define the ozone max/min. Can the authors provide some information about the models differences that the reader should be aware of in order to help interpret Fig. A2.

AR 1.2 We assume the reviewer is referring to high ozone cases (instead of low ozone cases) in SOCOL, where a double peak in the seasonal ozone evolution can be seen in Fig. A2. To exclude that this double peak structure and the strong ozone minimum simulated by SOCOL result from the chosen method of selecting high and low ozone cases based on 5-day running mean ozone values, we reproduced Fig. A2 by selecting high and low ozone springs based on 15-day running mean ozone values, as shown in Fig. R3. Figure R3 is largely similar to Fig. A2, which suggests that the methodology of defining high and low ozone cases is not the cause for model differences in the structure of the ozone evolution. Rather, systematic differences between WACCM, SOCOL and MERRA2 have to be considered to explain the origin of the different seasonal ozone evolution among models. Possible causes for the different structures in Fig. R3 and Fig. A2 are:

- Sudden stratospheric warming (SSW) frequency: In SOCOL, the SSW frequency in February and March is 0.46/year, whereas it is lower in WACCM (0.32/year) and MERRA2 (0.36/year). In Fig. 8 it can be clearly seen that SOCOL on average shows a SSW at 10 hPa in high ozone springs (Fig. 8f,g), whereas this is not the case in WACCM (Fig. 8a,b). The double peak structure in Figs. R3 and A2 in high ozone years in SOCOL could therefore be a consequence of the higher SSW frequency in this model, with one peak being due to SSWs in spring, whereas the second peak

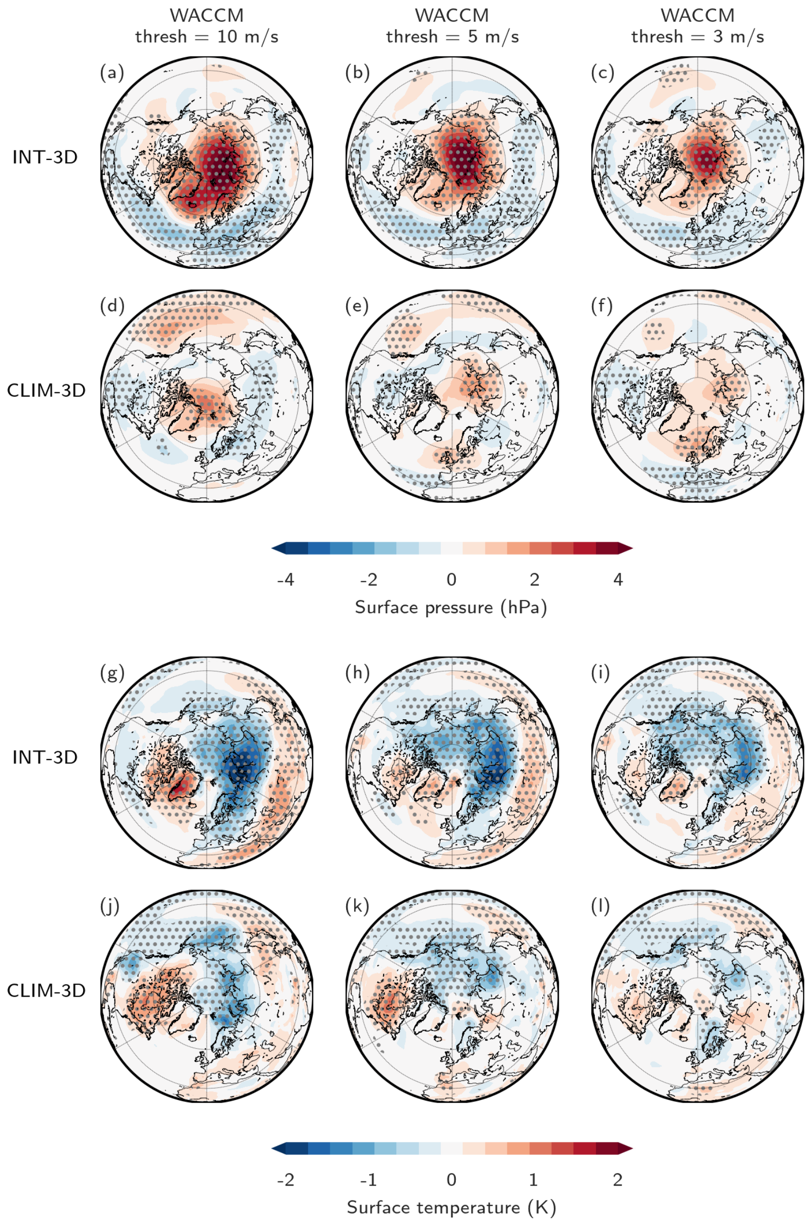

Figure R1: **Sensitivity of surface response to FSW threshold in high ozone springs.** Sea level pressure (SLP) (a-f) and surface temperature (g-l) anomalies in the 30 days following the 50-hPa FSW defined by different thresholds (10 m/s (left column), 5 m/s (middle column), 3 m/s (right column)) in high ozone springs WACCM INT-3D and CLIM-3D. Stippling shows significance on a 4.5% level following a bootstrapping test.

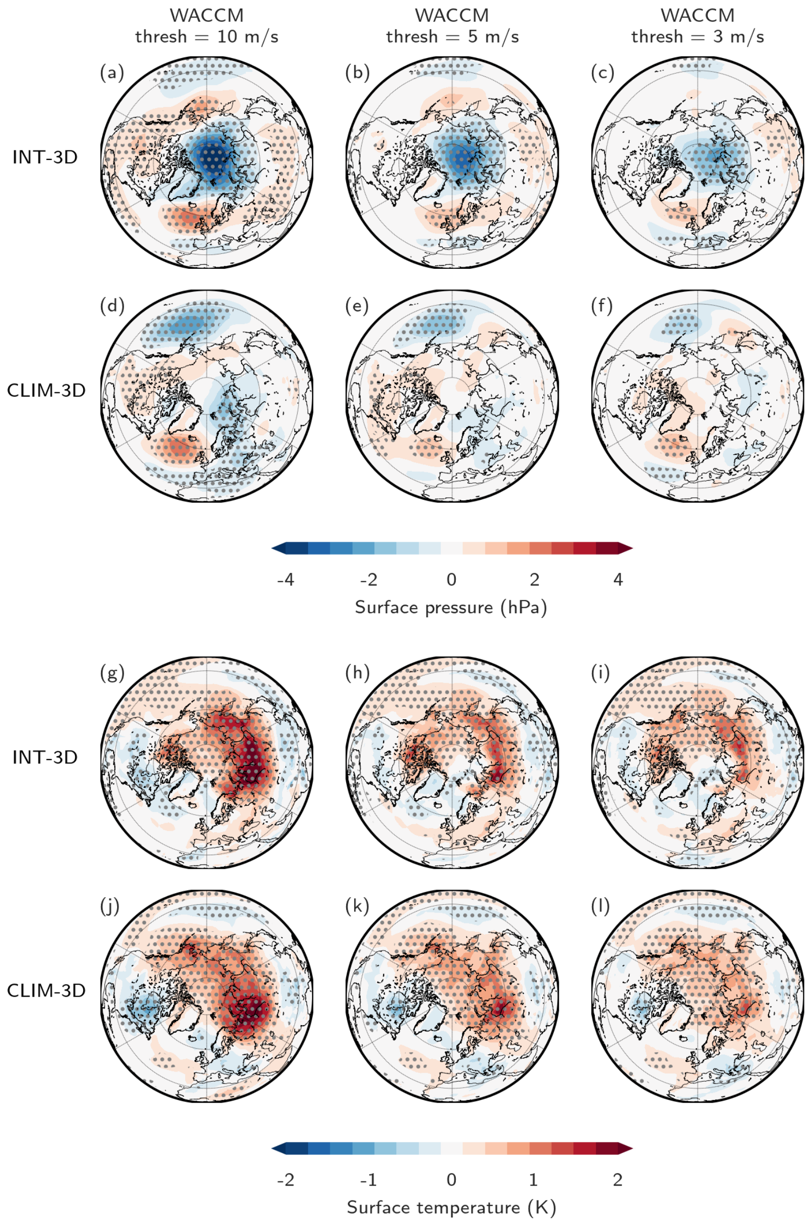

Figure R2: **Sensitivity of surface response to FSW threshold in low ozone springs.** SLP (a-f) and surface temperature (g-l) anomalies in the 30 days following the 50-hPa FSW defined by different thresholds (10 m/s (left column), 5 m/s (middle column), 3 m/s (right column)) in low ozone springs WACCM INT-3D and CLIM-3D. Stippling shows significance on a 4.5% level following a bootstrapping test.

might be due to the polar vortex breakdown.

- Timing/Extent of the ozone minimum: In WACCM, the ozone minimum happens only in mid-April, around one month later than in SOCOL. Therefore, the time lag between the ozone minimum and the FSW date, on average, is small in WACCM. As such, ozone has no time to recover (via dynamical re-supply) until the vortex breakup. In SOCOL, the ozone minimum happens already in March and therefore there is a longer time span (i.e., more than one month) between the ozone minimum and the FSW. Therefore, ozone values can recover before the spring onset, leading to a clear pronounced minimum.
- Polar vortex strength: As seen in Fig. A1, both models overestimate the strength of the climatological westerly wind at 50 hPa (black lines), with SOCOL having a stronger cold vortex bias (and thus stronger vortex) in low ozone cases. This might be a reason for the overestimation of the ozone minimum in this model.
- Eddy heat flux: the eddy heat flux at 100 hPa is commonly used as a proxy for planetary wave propagation. In SOCOL, there are negative eddy heat flux anomalies in late winter/early spring in low ozone springs exceeding anomalies in MERRA-2, which is probably the reason for the strong polar vortex bias in low ozone years in this model (Fig. A5).

In principle, it is possible with the chosen methodology of selecting high and low ozone springs to get overlapping years, i.e. having one year with both an ozone minimum and maximum. In practice, however, it never happens in WACCM, while it only happens twice in SOCOL. This suggests that maximum/minimum 5-day running mean ozone values are a good indicator for the overall springtime stratospheric ozone content in those years.

RC 1.3 3. Figure 3: Why do the authors choose a window up to 1 week after the FSW to examine the impact of preceding ozone on the FSW date? Also figure caption says starting from March 1st, while the text (line 216) says Feb. 20th.

AR 1.3 Thank you for this comment. The date in the figure caption of Fig. 3 is a mistake and should read "Feb. 20th". This has been corrected. The motivation for choosing a window up to one week after the FSW was that the maximum extent of the positive ozone anomalies based on daily values often coincides with the FSW date. However, we agree that this method might be confusing and causality (impact of ozone on the timing of the FSW) can only be inferred from ozone values before the FSW. We therefore changed our methodology and select now ozone values based on 5-day running mean values before the FSW date, as shown in Fig. R4. The correlation with this new method used in Fig. R4 is reduced compared to the previous Fig. 3, since ozone anomalies induced by the FSW itself are now excluded by only considering ozone values until the onset of the FSW. However, the

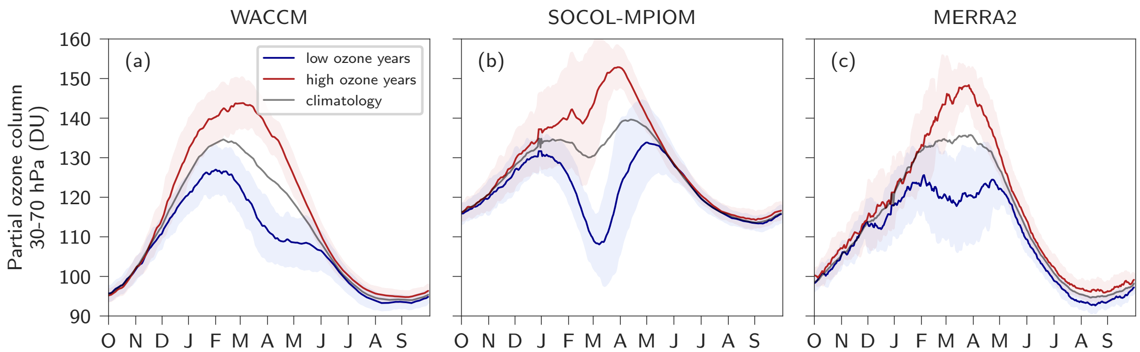

Figure R3: **Ozone evolution in high and low ozone years.** Evolution of ozone over the year in the 25% of years with the lowest (blue) and highest (red) springtime partial ozone column values between 30 and 70 hPa selected based on a 15-day running mean in (a) WACCM INT-3D, (b) SOCOL-MPIOM INT-3D, and (c) MERRA2. The grey line shows the climatology over all years in the respective datasets (200 years for WACCM and SOCOL-MPIOM, and 41 years for MERRA2). Shaded areas show the standard deviation across high/low ozone years.

differences between INT-3D and CLIM-3D in terms of correlation and regression slope are almost identical in Figs. R4 and former Fig. 3, emphasizing the robustness of the result. Figure R5 shows bootstrapping composites based on the new methodology, replacing former Fig. A3 in the manuscript.

RC 1.4 4. Connection to Haase and Matthes (2019): The feedbacks discussed in Section 3.3 are mainly positive. However, in the paragraph staring from line 340, the authors draw a connection between their results and the negative feedback discussed in Haase and Matthes (2019), but not explicitly. It might be useful to provide a bit more of a comparison between that study and this one and how the experimental setup differs (this could be noted in Section 2.1).

AR 1.4 Thank you for this comment. Haase and Matthes (2019) describe mechanistically how interactive ozone chemistry can impact stratospheric dynamics. In the case of negative ozone anomalies, for example, they describe how planetary wave propagation can either be enhanced or decreased depending on the background strength of the polar vortex. When the stratospheric background wind is weak (like during spring conditions), ozone minima lead to a colder stratosphere and a stronger polar vortex, but also to an increase of planetary wave dissipation, consequently disturbing the vortex and strengthening the BDC, leading to an increased transport of ozone to the poles ("negative feedback" on ozone itself, see Fig. 1 in Haase and Matthes, 2019). Haase and Matthes (2019) thereby

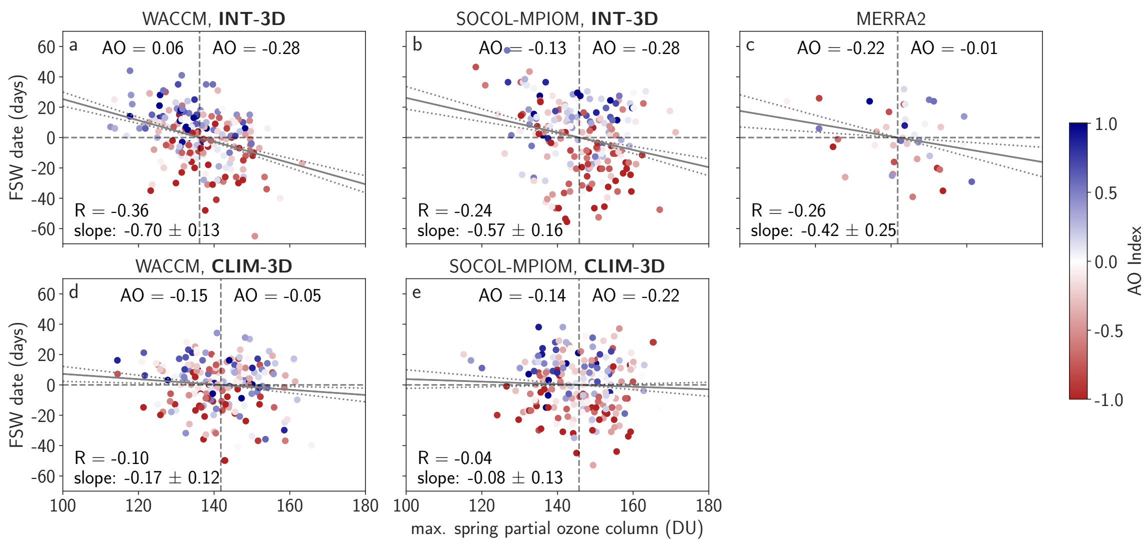

Figure R4: **Correlation of the FSW date and preceding spring ozone.** Linear regression of the maximum 5-day running mean partial ozone column between February 20th and the FSW in the respective year in WACCM INT-3D (a), SOCOL-MPIOM INT-3D (b) and MERRA2, as well as in WACCM CLIM-3D (d) and SOCOL-MPIOM CLIM-3D (e). Colors represent the AO Index in the month after the FW date, grey solid lines the linear regression lines. "R" denotes the Pearson correlation coefficient. Vertical grey stippled lines mark the mean ozone value over all years. Mean AO Indices are given for years with especially high (left) or low (right) ozone.

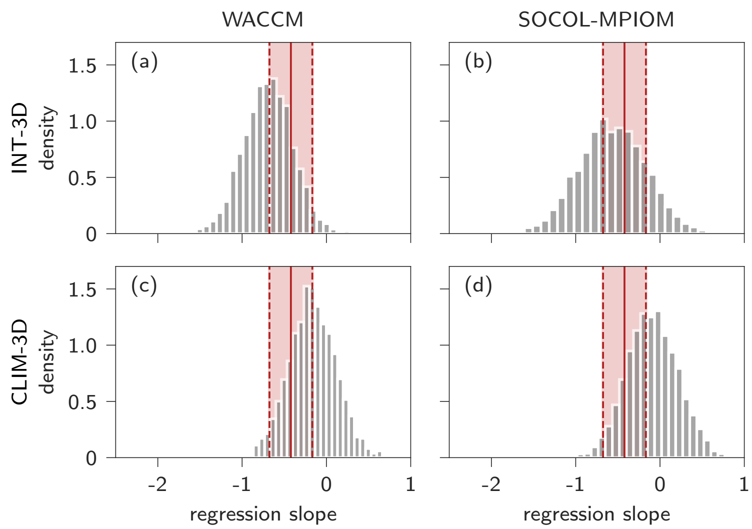

Figure R5: **Regression slopes in model simulations and reanalysis.** Regression slope of the maximum 5-day running mean partial ozone column (30-70 hPa) on the FSW date following Fig. R4 for 5000 samples consistent of 40 randomly selected years each for both sets of model simulations. The regression slope of the reanalysis is shown by the red solid line with its standard error indicated by the red shaded area.

use the term ”negative feedback” to describe the feedback of ozone on itself and do not specify any altitude dependence of the impact of ozone on planetary wave dissipation. In our manuscript, we refer to the ”negative feedback” terminology for cases with both low and high ozone concentrations and further discuss the altitude dependence of this feedback mechanism. For example, high ozone anomalies warm the lower stratosphere and weaken the vortex, which under springtime conditions inhibits planetary wave propagation to the upper stratosphere (above $\sim$ 10 hPa), where thus winds are strengthened (analogue to the “negative feedback” described in Haase and Matthes (2019)). However, a decrease in planetary wave propagation to the upper stratosphere means that planetary waves dissipate already at lower altitudes in the stratosphere (below $\sim$ 10 hPa), where they further decrease the polar vortex strength. The sign of the feedback of ozone on planetary waves is thus altitude-dependent. Thus, our description of ozone feedbacks does not contradict the terminology used by Haase and Matthes (2019), but rather is an extension of it.

We adapted the respective text in the manuscript to:

In addition to these processes, the weakening of the polar vortex by ozone in high ozone springs has further implications for planetary wave propagation. Around the onset of the FSW, when the westerly winds are weak, further deceleration of westerly winds in the lower stratosphere by ozone leads to a dissipation of planetary waves already at lower altitudes, amplifying the heating due to radiative processes (shortwave absorption). As the propagation of planetary waves through the stratosphere is thereby reduced, less wave dissipation takes place in the upper stratosphere, where zonal winds are thereby enhanced. This mechanism is analogous to the ”negative feedback” described in Haase and Matthes (2019). The enhanced wave dissipation in the upper stratosphere compensates for the shortwave heating effects in this region, so that feedbacks arising from the coupling between ozone and the circulation do not significantly affect the timing of the FSW in the upper stratosphere (see Fig. 2 INT-3D vs. CLIM-3D). Rather, ozone shifts the FSW below $\sim$ 10 hPa to earlier dates (via the impacts on shortwave heating and planetary wave breaking).

References to Haase and Matthes (2019) highlighting differences in the experiment setup compared to our study have now been included in the methods section (section 2.1).

RC 1.5 Technical Notes:

Line 4: Final Stratospheric Warming not Stratospheric Final Warming if you want to use the FSW short-hand

AR 1.5 Thank you, this has been corrected in the abstract.

RC 1.6 Line 11: lacking $\rightarrow$ the lack of

AR 1.6 This has been adapted.

RC 1.7 Line 217: "...one week after the FSW in each year..."

AR 1.7 This part has been adapted according to the new methodology used in the linear regression (Fig. 3).

RC 1.8 Line 262: "Ozone thereby contributes..."

AR 1.8 This has been corrected.

RC 1.9 Line 290: "...wave driving across the models..."

AR 1.9 This has been corrected.

RC 1.10 Figure 6: y-axis labels should be: INT-3D and CLIM-3D, not INT-O3 and CLIM-O3

AR 1.10 Thank you, this has been corrected. Note that this Figure is now shown as part of the appendix.

RC 1.11 Line 311: also Tegtmeier et al. (2008): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008GL034250

AR 1.11 Thank you, this paper is now cited in the manuscript.

RC 1.12 Line 334: I think you are referring to Figures 7 a, b and f, g here.

AR 1.12 Yes, thank you. This has been corrected.

RC 1.13 Figure A4: add MERRA2 data for comparison

AR 1.13 Thank you for this recommendation. MERRA2 has been added to Figure A4.

Reviewer 2

RC 2.1 Friedel et al investigate the connection between stratospheric ozone anomalies, the final warming or breakdown of the stratospheric polar vortex, and subsequent surface impacts. The key novelty of this work is that the authors compare simulations in which the radiative scheme reads in vs. ignores daily variability driven by the dynamics of each particular winter, and hence are able to isolate key feedbacks between ozone and dynamics. These simulations are performed for two different models, which enhances the robustness of their conclusions

The foundations of a paper that could be published in ACP are clearly present, and two of the three subsections in the results section are generally convincing. The last is still incomplete however, as described below. However, this last subsection can be improved with additional analysis of already existing simulations, and hence the required revisions should be relatively straightforward to perform. After these are addressed this paper should be publishable.

Major comments:

The authors pose the question "2) Is there a significant influence of ozone on the surface response to FSWs?;" on line 67, but I don't think section 3.2 answers this question fully. Section 3.1 convincingly demonstrates that FSWs are indeed modified by ozone, however this conclusion is not reflected in the methodology the authors then use in section 3.2.

Section 3.1 demonstrates that the CLIM experiments simulate a narrower PDF of dynamical variability in the polar vortex, with a narrower distribution of FSW dates. Hence, by selecting the top 25% and bottom 25% of ozone anomalies, and then studying the surface impacts, the authors are baking in a larger dynamical stratospheric perturbation in INT-3D than in the CLIM runs, and hence it is obvious (at least to me) that the surface impacts would be larger in INT-3D than in CLIM (e.g. Harari et al 2019) with the present methodology.

In order to isolate an ozone impact on surface climate, the methodology should be different. In addition to (or instead of) the current Figures 4 and 5, can the authors try compositing years with ozone anomalies of, say, between +20 to +40 DU vs. -20 to -40DU in both CLIM and INT-3D, and then study whether the difference in surface response between the high and low ozone years depends on how ozone is treated? This would more carefully isolate the role of ozone anomalies for surface impacts, and isolate whether the surface impact is via ozone affecting dynamics vs. ozone affecting tropospheric processes directly. That is, does a given strengthed ozone anomaly lead to the same surface impact regardless of whether ozone is interactive, or is the interactive ozone crucial?

AR 2.1 Thank you for this comment. We agree with the reviewer that the distribution of FSW dates in the lower stratosphere is wider in simulations including interactive ozone (INT-3D) compared to simulations employing an ozone climatology (CLIM-3D), as seen in Fig. 2 in the manuscript. There are three points in this context that we would like to clarify:

- The wider distribution of FSW dates in simulations where interactive ozone is being calculated (INT-3D) is a direct consequence of the ozone anomalies, which influence the stratospheric dynamics via shortwave heating, thereby increasing dynamical variability. In contrast, the CLIM-3D experiments, though computing ozone interactively (used in the model chemistry), do not couple it radiatively (and it therefore does not influence shortwave heating and longwave cooling) but use an ozone climatology for this purpose. Therefore, the difference between both simulations isolates the impact of ozone anomalies on the variability of FSW dates.
- As correctly pointed out by the reviewer, the larger variability in the FSW date and larger stratospheric anomalies in INT-3D around the FSW date are the cause for the observed larger surface anomalies in these experiments. While it might seem obvious that larger stratospheric anomalies (as a direct cause of the ozone anomalies) cause a larger surface impact in INT-3D, our study is to the best of our knowledge the first one showing a clear causal connection between ozone anomalies, stratospheric dynamics and surface climate in the context of FSWs.
- The ozone anomalies, as calculated by the chemistry module in both INT-3D and CLIM-3D, are of very similar magnitudes across the 50 high and low ozone cases in our two models, as shown in Fig. R6. Therefore, the reviewer's suggestion to select ozone anomalies of similar magnitude in INT-3D and CLIM-3D is already being addressed with the current methodology. In this context, one might also ask whether imposing ozone anomalies (instead of an ozone climatology) would make a difference in terms of the timing of the FSW and associated surface impacts compared to using interactive ozone chemistry (and thereby isolating the effect of the "interactiveness" of ozone in the model). While this is a very interesting issue on its own, this not the question we seek to answer in this study. Rather, we are studying the effect of interactive ozone chemistry compared to a setting where the ozone is fixed to climatological values (as still done by many weather and climate models).

Thus, with the current methodology, we demonstrate that ozone anomalies impact the surface response of FSWs via their enhancement of stratospheric anomalies. Therefore, we show that interactive ozone chemistry improves the representation of springtime surface climate in chemistry-climate models compared to simulations with prescribed climatological ozone.

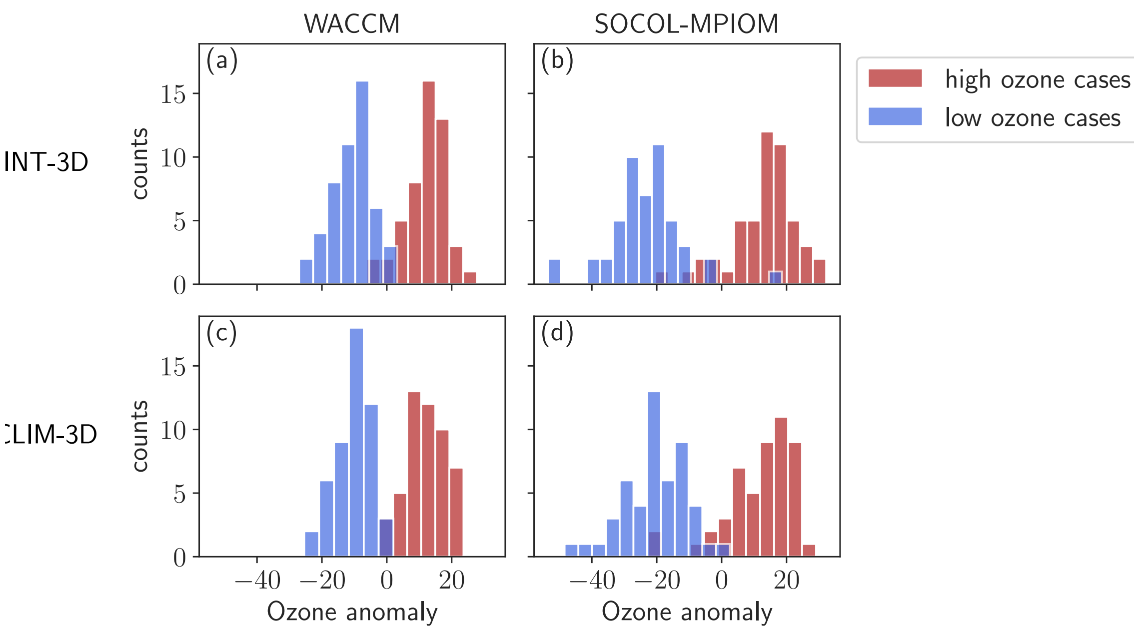

Figure R6: **Comparison of ozone anomalies in INT-3D and CLIM-3D.** Anomalies of partial stratospheric ozone column (30-70 hPa) at the ozone maximum/minimum date based on 5-day running mean in the 50 high (red) and low (blue) ozone springs in WACCM (left column) and SOCOL (right column) in simulations with interactive (upper panel) and climatological (lower panel) ozone.

RC 2.2 2. The discussion section should include a more thorough comparison of the results from this paper to those of Friedel et al 2022 in Nature Geo. Specifically, it is perplexing (at least to this reviewer) that the NatureGeo paper found that low ozone has a surface impact, while the present paper finds low ozone has little surface impact when viewed through the lens of final warmings (lines 265 to 271 and figure 5). As best as I can tell the identical simulations are analyzed in both, and the authorship list is essentially the same as well. Does that imply that low ozone has a surface impact but FSW distorts this impact somehow? The authors need to help the reader sort out this conundrum.

AR 2.2 The original Fig. 6 in the manuscript and the text following line 272 explain the connection between the surface impact of ozone minima (as described in Friedel et al., 2022) and the subsequent surface impact of FSWs in those years. We realize that this paragraph and the supporting Figure might not have been clear enough. We replaced the original Fig. 5 in the manuscript by Figs. R7 and R8 showing the seasonal evolution of the surface signal in high and low ozone years in WACCM. The original Fig. 5 is now included in the appendix. In low ozone years, the ozone minimum occurs on average mid April, after which SLP anomalies start to emerge at the surface (Fig. R7). Those anomalies are larger in magnitude when interactive ozone is included in the simulations, showing a clear imprint of ozone depletion on surface climate (compare upper and lower panel in Fig. R7). This enhancement of surface anomalies by interactive ozone following ozone minima is what has been previously reported by Friedel et al. (2022). With occurrence of the FSW in the first half of May, the signal starts to decay. The FSW interferes with this signal by decreasing the SLP over the Arctic, effectively canceling the signal of the preceding ozone minimum by June.
In high ozone years, a significant SLP pattern only starts to emerge after the occurence of the FSW in mid April, as seen in Fig. R8. As in low ozone cases, the FSW in high ozone years acts to increase the SLP anomalies over the North pole, suggesting that the FSWs are in general followed by an increase of polar SLP anomalies, and thus a shift of the AO index towards negative polarity.
To make the connection between the surface impacts of ozone minima and FSWs clearer, we replaced Fig. 5 in the manuscript by Figs. R7 and R8 and adapted the respective text (following line 272) as follows:

The analysis so far focuses on the 30-day averaging after the onset of the FSW, which masks considerable intra-seasonal variability. To gain additional insights onto the role of precursors, we analyze the seasonal evolution of the SLP signal (Figs. R7, R8). For low ozone cases, the SLP anomaly already emerges in the first half of April and maximizes mid-April — almost 1 month before the mean FSW date in those years (May 10). FSWs in low ozone springs therefore tend to be preceded by SLP anomalies resesmbling a positive AO. The surface pattern in low ozone years is thereby not a consequence of the FSW, but results from the preceding ozone minimum, which strengthens the polar stratospheric vortex,

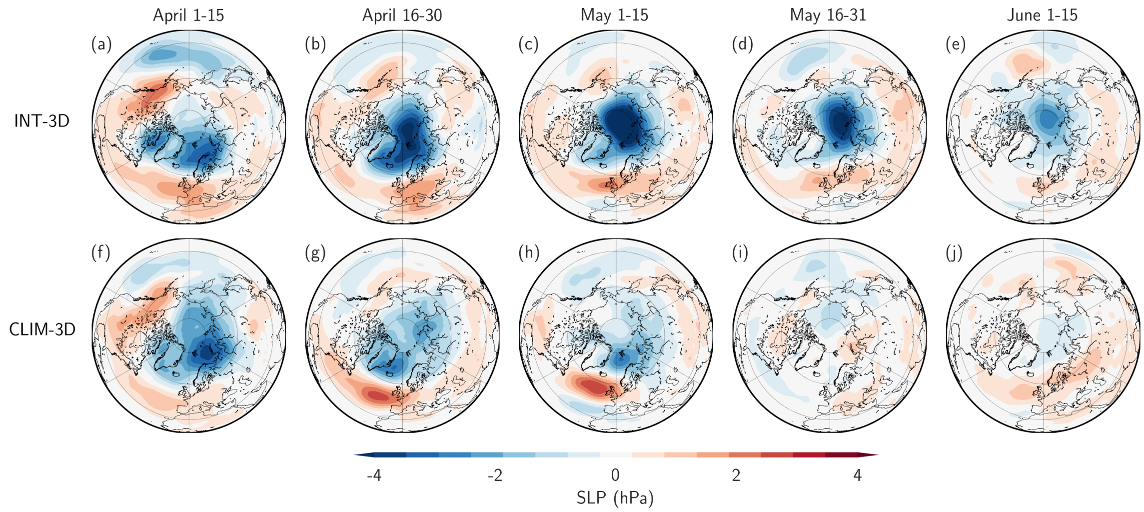

Figure R7: **Seasonal evolution of SLP anomalies in low ozone years in WACCM.** Evolution of SLP anomalies from April to June in low ozone springs in WACCM simulations with interactive ozone chemistry (a-e) and climatological ozone (f-j). The mean ozone minimum date is mid April, the mean FSW date in INT-3D simulations is May 10.

resulting in a shift towards a positive AO at the surface (Friedel et al, 2022). Since surface anomalies are more pronounced in simulations including interactive ozone (compare top vs. bottom panels in Fig. R7), it can be concluded that the negative ozone anomalies are the cause for the positive AO pattern in low ozone years. With the onsest of the FSW (on average on May 10), in turn, the SLP anomalies start to decay and the AO signal decays by mid June. The FSW therefore counteracts the surface effects of the ozone minima and offsets their AO response at the surface. Similarly, for high ozone cases, a shift towards a negative AO pattern can be seen after the onset of the FSW in mid-April (Fig. R8), which is more pronounced in simulations which employ interactive ozone. This shift towards a negative AO following the FSW in both low and high ozone springs is consistent with previous findings reporting a decrease of the AO index following FSWs (Thieblemont et al., 2019).

RC 2.3 Minor comments:

There are a few recent papers showing that include interannual or intraseasonal ozone variability in a model helps improve forecast skill for the Southern Hemisphere (Oh et al 2022, Hendon et al 2020). I realize this study is focused on the NH, however these papers should be included and discussed.

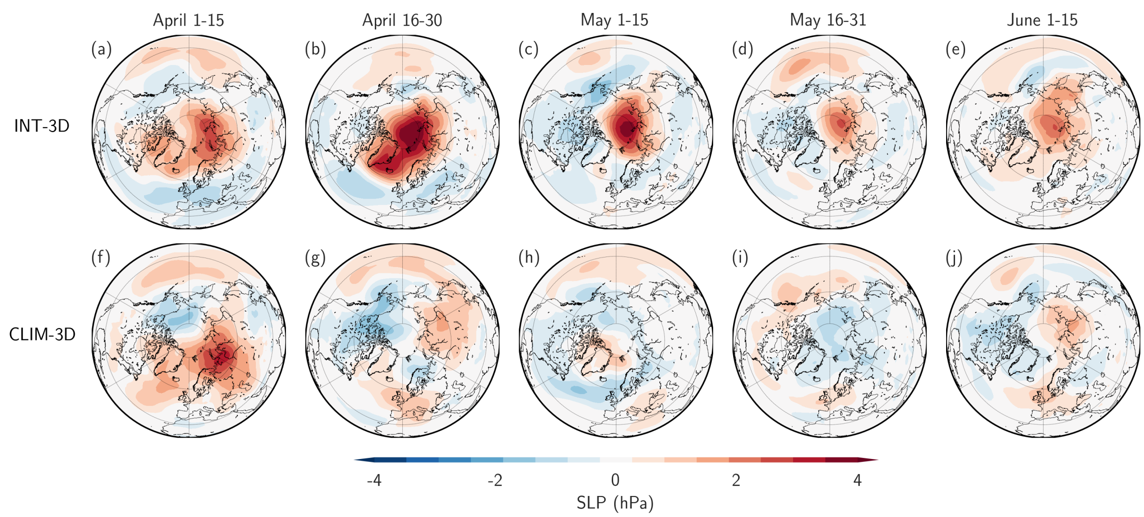

Figure R8: **Seasonal evolution of SLP anomalies in high ozone years in WACCM.** Evolution of SLP anomalies from April to June in high ozone springs in WACCM simulations with interactive ozone chemistry (a-e) and climatological ozone (f-j). The mean ozone maximum date is beginning of March, the mean FSW date in INT-3D simulations is April 17.

AR 2.3 Thank you for this suggestion. Those studies are now discussed in the introduction following line 62:

Recent modelling studies on the Southern Hemisphere already show promising results, with an improvement of forecast skill on seasonal scales arising from stratospheric ozone (Hendon et al. (2020), Oh et al. (2022)).

RC 2.4 Line 70 "Finally" → "Next" (this isn't the final item yet)

AR 2.4 Thank you, this has been adjusted.

RC 2.5 Line 300 "In summary" is an odd way to begin a sentence before the results are actually shown. Maybe instead, "Briefly, we will demonstrate that . . . "

AR 2.5 This has been adjusted.

RC 2.6 Line 352 What about the upper stratosphere, especially in WACCM? Why is the radiative heating anomaly opposite? More generally, it would be nice if the authors could show all terms in the TEM thermodynamic budget in order to understand better how the differences arise. However the paper is publishable even without such additional analysis.

AR 2.6 Thank you for this comment. Indeed, the positive radiative heating anomaly in the former Fig. 8 d) in the manscript might be surprising and is an artefact of different model variables used for WACCM INT-3D and CLIM-3D. While for CLIM-3D only the pure shortwave heating rate ("QRS") is available on daily resolution, for INT-3D only a merged variable ("QRS_TOT" including, among others, a diabatic heating term and CO2 near-infrared heating) is available. While the climatologies of those two variables are slightly different and lead to the positive difference in shortwave heating in Fig. 8 d), anomalies in both variables are mainly driven by ozone. In Fig. R10 it can be seen that in simulations with prescribed ozone, anomalies in the shortwave heating are negligible, whereas there are strong anomalies in simulations with interactive ozone. Those anomalies in shortwave heating follow almost perfectly the ozone distribution in high and low ozone springs in both WACCM and SOCOL, as seen in Fig. R9, suggesting that ozone is the main (if not the only) source of the shortwave heating anomalies. We included R9 in the appendix, which links the shortwave heating pattern directly to the vertical ozone anomalies. With this, we think it is not necessary to show all terms in the TEM thermodynamic budget to explain the shortwave heating pattern. Further, we now show differences in shortwave heating anomalies (instead of absolute differences) in former Figs. 7 and 8 in the manuscript to account for the slightly different climatologies of the model variables "QRS" and "QRS_TOT" in WACCM.

Harari, Ohad, Chaim I. Garfinkel, Shlomi Ziskin Ziv, Olaf Morgenstern, Guang Zeng, Simone Tilmes, Douglas Kinnison et al. "Influence of Arctic stratospheric ozone on surface climate in CCMI models." Atmospheric Chemistry and Physics 19, no. 14 (2019): 9253-9268.

Hendon, H. H., E.-P. Lim, and S. Abhik. "Impact of interannual ozone variations on the downward coupling of the 2002 Southern Hemisphere stratospheric warming." Journal of Geophysical Research: Atmospheres 125, no. 16 (2020): e2020JD032952.

Oh J., S-W Son, J. Choi, E-P. Lim, C I. Garfinkel, H. Hendon, Y. Kim, H-S. Kang, Impact of Stratospheric Ozone on the Subseasonal Prediction in the Southern Hemisphere Spring, Progress in Earth and Planetary Science, doi: 10.1186/s40645-022-00485-4.

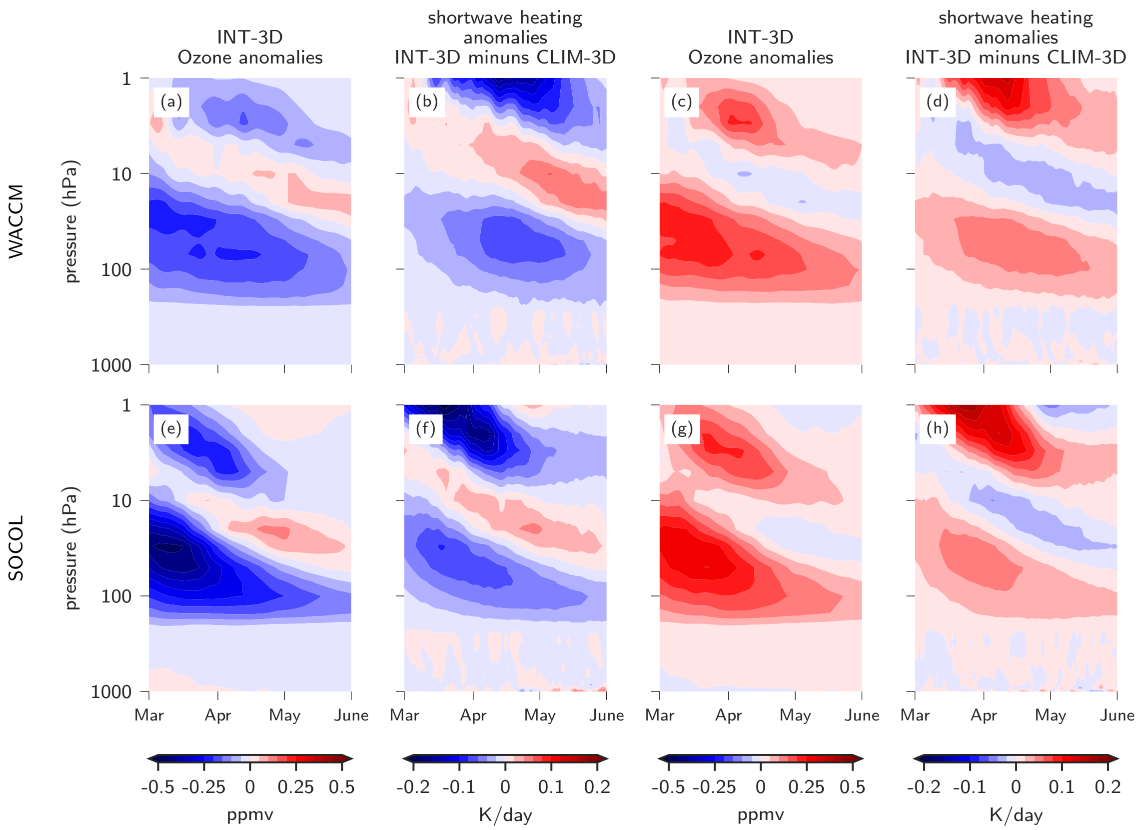

Figure R9: **Ozone and shortwave heating anomalies in high and low ozone springs.** Ozone anomalies in experimentes with interactive ozone chemistry in low (a, e) and high (c, g) ozone springs as well as differences in shortwave heating anomalies between INT-3D and CLIM-3D in low (b, f) and high (d, h) ozone springs in WACCM (upper panel) and SOCOL (lower panel).

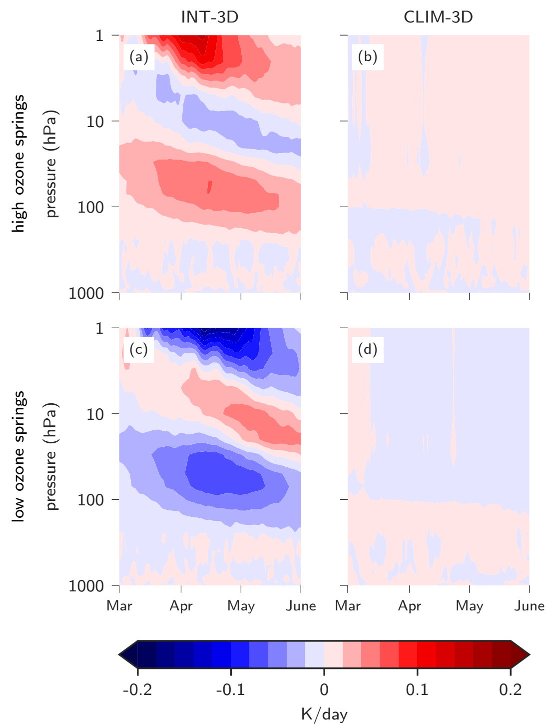

Figure R10: **Shortwave heating anomalies in WACCM.** Anomalies in shortwave heating in high (upper panel) and low (lower panel) ozone springs in WACCM simulations including (left column, model variable "QRS_TOT") and excluding (right column, model variable "QRS") interactive ozone chemistry.