Response to Referee's Comments

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Title: Effects of Ozone-Climate Interactions on the Long-Term Temperature Trend in the Arctic Stratosphere

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Summary of revision in manuscript

We sincerely thank the two reviewers for their important comments and assistance on our manuscript. The main revisions are summarized as follows:

1. Following the reviewer's suggestions, we created a 1980-clim experiment with an initial field set to fixed boundary conditions for 1980. The climatological mean ozone from the 1980-clim experiment is imported into the radiation scheme of the O3clm experiment. Then, we rerun the O3clm experiment.

2. The two reviewers mentioned that only one experiment was unable to exclude the effect of interannual variability in the long-term trend. It was suggested that more ensemble experiments should be conducted. Therefore, we conducted five ensemble experiments for the control and O3clm experiments using different initial fields to ensure the robustness and reliability of the results in the revised manuscript.

3. A detailed description of the experiments has been added to the revised manuscript. Please see method section 2.3: Model and experimental configurations.

4. Some sentences have been rewritten as well as the grammar is improved throughout the manuscript.

Response to Comments of Reviewer #1

I appreciate the authors efforts to isolate the impact of past Arctic ozone changes on trends in temperature and dynamics and to underline their findings with mechanical explanations. Unlike other studies, this study focuses on the extended winter season and might therefore extent our knowledge on the impacts of ozone changes from springtime to the whole winter season. However, I have doubts around the entire experiment setup (especially the way the ozone climatology is calculated) and think that the conducted simulations are not suitable to achieve the goal of this study. Moreover, the authors make use of a figure from another study without mentioning it.

Response: We are sincerely grateful for the insightful comments and constructive suggestions provided by Reviewer #1. In response to the feedback from Reviewer #1 and the community, we have conducted new ensemble experiments and incorporated supplementary discussions with physical interpretations in relevant sections to enhance the manuscript's clarity. The introduction section has also been strengthened to better emphasize the significance of this study. We apologize for the extended review cycle due to the high computation costs of the ensemble experiments for control and O3clm experiments.

Main comment #1:

More details should be provided on the ozone climatology that is used in the O3clim experiments. Are these daily or monthly means? 3D or zonal mean? If I understand it correctly from Fig. 1, then the ozone chemistry is still calculated in the O3clim setup, but it is not radiatively active. This information is missing in the experiment description in lines 179. How many ensemble members were simulated? Moreover, Fig. 1 is identical to Fig. 1 from Friedel et al. (2022b) and the caption accompanying this figure is almost identical to the caption of Fig. 1 in Friedel et al. (2022a). This must be cited!

Response: We thank the reviewers for your comments. We have expanded the experimental description in the main text and incorporated their suggestions. In the previously submitted manuscript, we used one ensemble experiment, and for

the robustness of the experimental results and at the same time to reduce the uncertainty in the effects of ozone-climate interactions, in the revised manuscript we added five ensemble experiments for the new control experiment and the new O3clm experiment. Ensemble members have identical boundary conditions and radiation scheme, but with different initial conditions, which account for the internal variability of the climate system. We have added this specific information in the revised manuscript. Here is revised text as follows (Please see lines 244-261 in the revised manuscript):

**"*To understand the causality of the ozone-circulation coupling, we perform model experiments to isolate the impact of ozone changes on stratospheric dynamics and circulation. Two groups of ensemble climate model experiments (i.e., the control experiment and O3clm experiment) use identical boundary conditions and initial conditions. Each group simulation consists of 5 ensemble members, with initial temperature conditions randomly perturbed. Both of the two experiments run from 1970–2020, and the first 10 years are the spin-up time. The control experiment uses fully interactive ozone chemistry, and long-term stratospheric ozone changes are involved in the radiation scheme. In contrast, in the O3clm experiment, the climatological mean ozone is represented by monthly 3-dimensional mean data from a 1980-clim experiment, which is imported into the radiation scheme. In the 1980-clim experiment, surface emissions, external forcing, stratospheric aerosols, fixed lower boundary conditions, and the solar photon enerspectra are all fixed at 1980. The 1980-clim experiment runs for 40 years with the first 10 years as spin-up time and the remaining 30 years of data are used to drive the radiation scheme of the O3clm experiment. This results in the production of fixed radiative feedback, which is to say that the ozone-climate interactions over a long period are not radiatively active. Meantime, this setting is designed to preserve the seasonal temperature variations that conform to the background environmental conditions of the Earth and ensure stable operation of the experiment. Thus, the comparison between the ensemble mean of control and O3clm experiments isolates the feedback effects of*

***long-term stratospheric ozone changes on atmospheric temperature and circulation from climate variability. Figure 1 (adapted from Friedel et al. 2022a, 2022b) provides the inspiration for the experimental design, which is crucial to understanding the analysis presented in this study.*"**

In addition, we sincerely apologize for the omission of Figure 1 in the original manuscript, which is similar to Figure 1 in Friedel et al. (2022b). We acknowledge that this figure is similar to Friedel et al. (2022b) and needs to be cited. In the revised manuscript, we have written the experimental design diagram for better understanding of the purpose of the experimental design. Furthermore, we have cited Friedel et al. (2022a; 2022b) to acknowledge their original work and contribution (see lines 264-268):

"*Figure 1 Simulation setup of the ensemble control and O3clm experiments. The control experiment treats ozone chemistry fully interactively. That is, the calculated ozone field has direct feedback on the atmosphere via the model radiation scheme. In contrast, the ensemble O3clm experiments do not use interactively calculated ozone in the radiation module. Instead, the radiation module uses an ozone climatology, which is derived from the 1980-clim experiment (see Method text) (This figure adapted from Fig. 3a in Friedel et al., 2022a and Fig.1 in Friedel et al., 2022b).*"

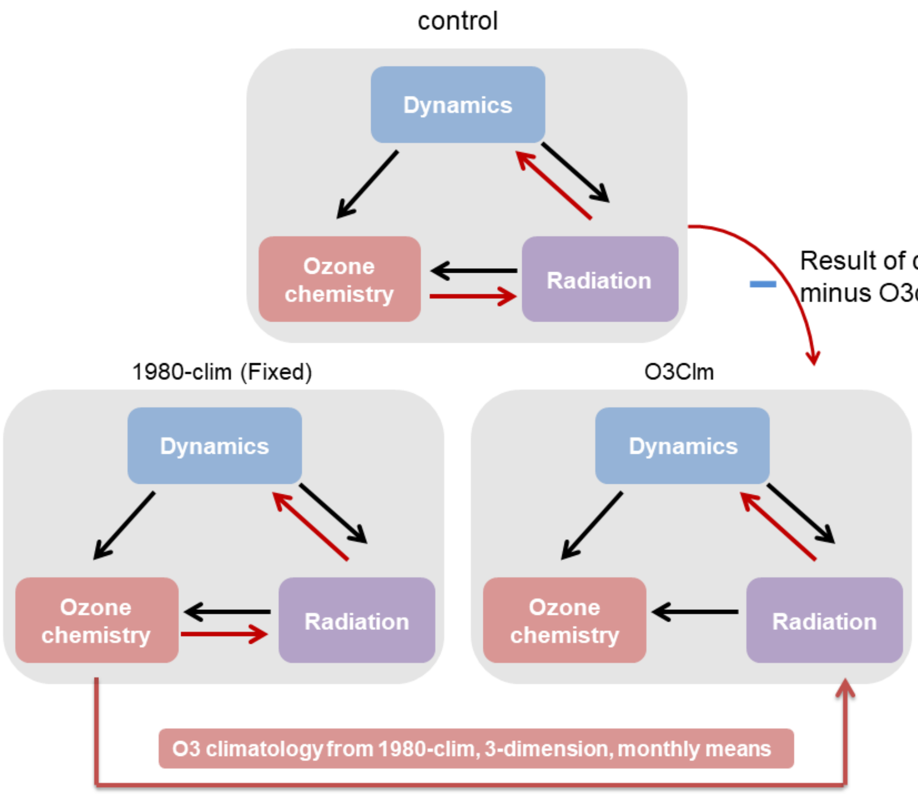

Figure R1. Simulation setup of the ensemble control and O3clm experiments. The control experiment treats ozone chemistry fully interactively. That is, the calculated ozone field has direct feedback on the atmosphere via the model radiation scheme. In contrast, the ensemble O3clm experiments do not use interactively calculated ozone in the radiation module. Instead, the radiation module uses an ozone climatology, which is derived from the 1980-clim experiment (see Method text) (This figure adapted from Fig. 3a in Friedel et al., 2022a and Fig.1 in Friedel et al., 2022b).

Main comment #2:

If I understand the experiment design correctly, I believe that the conducted simulations are not suitable to study the impact of past ozone changes on trends in temperature and dynamics. The authors contrast one simulation with fully interactive ozone for the period 1980-2020 against a simulation where they impose an ozone climatology calculated over this period. Then, they contrast trends from 1980-2000 in the two simulations to isolate the effect of ozone changes during that period on the variables of interest. I believe that this experiment design does not allow to disentangle the effect of past ozone changes, as the climatology was calculated over a period that includes ozone trends. Therefore, the ozone climatology used in the O3clim run might show lower ozone concentrations (due to an ozone decline from 1980-2000) than the ozone field in the crtl run in 1980. Hence, at the starting point of the simulations (i.e. 1980), the circulation/temperature and ozone field are not consistent in the O3clim simulation. Therefore, temperature changes might arise to adjust to the lower ozone concentrations and trends in this simulation cannot solely be attributed to dynamical and thermodynamical processes other than ozone. Moreover, with the approach used here, effects of potential long-term ozone changes and interannual ozone changes are mixed, since they are both disabled in the O3clim experiments. When only using one ensemble member of 20 years, the role of interannual ozone variability is likely not negligible.

In order to achieve the goal posed by this study, I suggest first deriving an ozone climatology using a time-slice simulation with fixed boundary conditions (i.e. CFCs, GHGs,...) of the year 1980 with fully interactive ozone. The ozone climatology calculated this way can then be used to simulate the O3clim experiments from 1980-2000. Using this approach, the authors would be able to attribute changes in dynamics and temperature over this period to changes in ozone. However, more than one ensemble member for the transient runs would be necessary in order to isolate the effect of longterm ozone changes rather than the effect of interactive ozone variability.

Response: Thank you for your detailed and thoughtful comments. The reviewer pointed out that the ozone climatology used in the current O3clm simulation may have been influenced by the negative trend in ozone during the 1980−2000 period. In the revised manuscript, we first conducted a 1980 ozone climatology experiment (1980-clim experiment) using 1980 fixed boundary conditions. The detailed information of experimental setup has been given in Major comment #1. The ozone output from the new O3clm experiment can reflect a stable baseline without ozone long-term trends, ensuring consistency between the ozone field in the O3clm

experiment at the start of the transient run and the circulation and temperature fields. It also removes the potential influence of long-term negative trends on the stratospheric circulations. We compare the climatological ozone from the 1980-clim experiment with the ozone from the control experiment in the original manuscript. The climatological ozone differences between the 1980-clim experiment and the control experiment for 1980−2020 and for different seasons are given in Figure R2. Note that the climatological ozone from the control experiment, that is used to force the old O3clm experiment in the previous manuscript, is lower than that in the 1980-clim experiment, imply a potential effect of negative ozone trend in the old O3clm experiment. Therefore, in the revised manuscript, we use the climatological ozone with seasonal cycle derived from the 1980-clim run as the ozone input field for the new O3clm experiment to exclude the effect of a negative ozone trend.

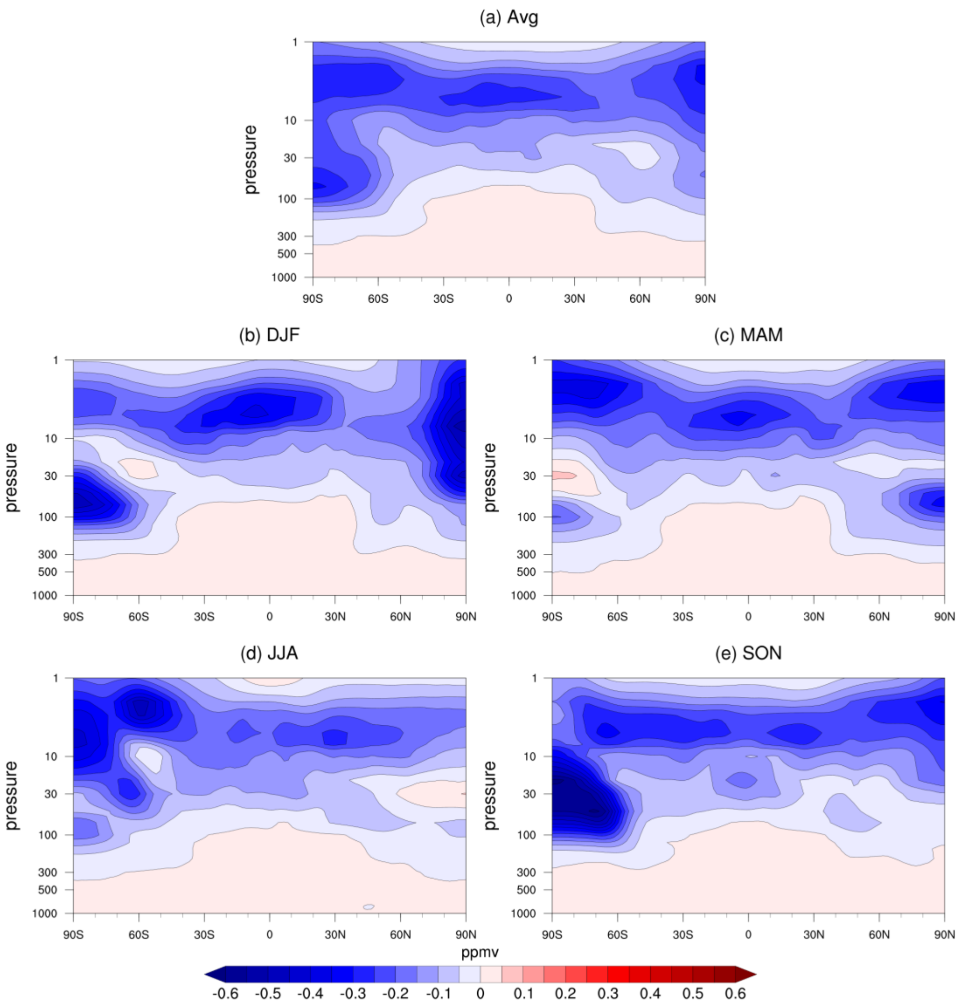

Figure R2. Differences in the climatological ozone (unit: ppmv) between the 1980-clim experiment of which climatological ozone forces the new O3clm experiment, and the control experiment of which climatological ozone forces the old O3clm experiment, shown for the annual mean (a), winter mean (December–February) (b), spring mean (March–May) (c), summer mean (June–August) (d), and autumn mean (September–November) (e).

The new O3clm experiment was also compared with a fully interactive ozone simulation (the control experiment) to accurately isolate the effects of ozone changes on temperature and its long-term trend. The reviewers suggested that the role of interannual ozone change may not be negligible. Therefore, in order to isolate the effects of long-term ozone trend from interannual ozone variability, we increased the number of ensemble members both for the control experiments and the O3clm experiments up to five, reducing the influence of interannual variability in the trend analysis. We have focused on analyzing the effects of long-term ozone changes on the temperature trend using the ensemble mean of the 5 ensemble members.

Figures R3 and R4 give the normalized time series and linear trends in Arctic stratospheric temperatures for different periods (before 2000 and after 2000) from early winter to early spring, with mean values ranging from 10 to 150 hPa. The control experiment in the original manuscript shown in Fig. R3 (hereafter referred to as 'old control experiment) is one ensemble member of the 5 ensemble control experiments, while Fig.4 shows the ensemble mean of the control experiments. A comparison of Fig.3 and Fig.4 (one ensemble member and ensemble mean of 5 members) shows that the added ensemble experiments do not substantially change the Arctic stratospheric temperature trend. From November to December, the Arctic stratospheric temperature from both the MERRA-2 and ERA5 reanalysis

datasets show a small positive trend before 2000 and an insignificant negative trend after 2000 (Figs. R3a, R4a; black line for MERRA-2 and grey line for ERA5). This suggests a warming trend in the Arctic stratosphere during early winter before 2000 and a cooling trend after 2000. The ensemble mean of the control experiments reproduce these opposite trends well, with a significantly positive trend in temperature before 2000 and a significantly negative trend after 2000 (Figs. R3a, R4a; purple line). From January to February, the temperature displays an insignificant negative trend before 2000 in the old control experiment (Fig. R3b) and a significant negative trend after 2000 in the ensemble control experiments (Fig. R4b). From March to April, the temperature from all three datasets shows a significant negative trend before 2000, while there is no significant trend after 2000 in the ensemble mean of the control experiments and the old control experiment (Figs. R3c, R4c). Overall, the long-term trends in temperature derived from the ensemble mean of control experiments are nearly consistent with the results of the reanalysis datasets, both in the period before 2000 and after 2000. In addition, the results of the ensemble mean of control experiments are similar to those of the previous control experiment in the original manuscript, but the ensemble mean of control experiments is able to exclude the internal variability of the climate system; therefore, we use the ensemble mean of the control experiments in the revised manuscript.

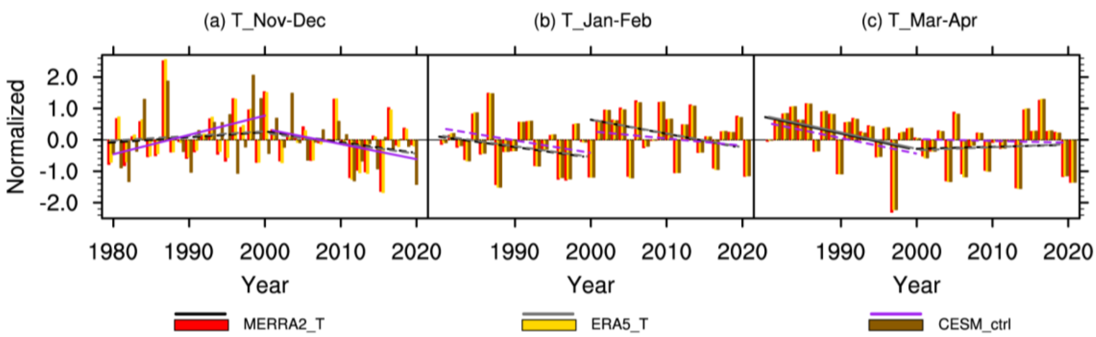

Figure R3. Normalized time series of the temperature averaged from 150 hPa to 10 hPa over 65°–90°N from 1980–2020 in (a) November–December, (b) January–February, and (c) March–April derived from the MERRA-2 (red column), ERA5

(orange column) reanalysis dataset and CESM control experiments used in the original manuscript (brown column). The color straight lines represent the linear trends during the pre-2000 and post-2000 periods. Solid lines indicate that the trends are statistically significant at the 90% confidence level according to Student's *t* test. This is Figure 2 in the original manuscript.

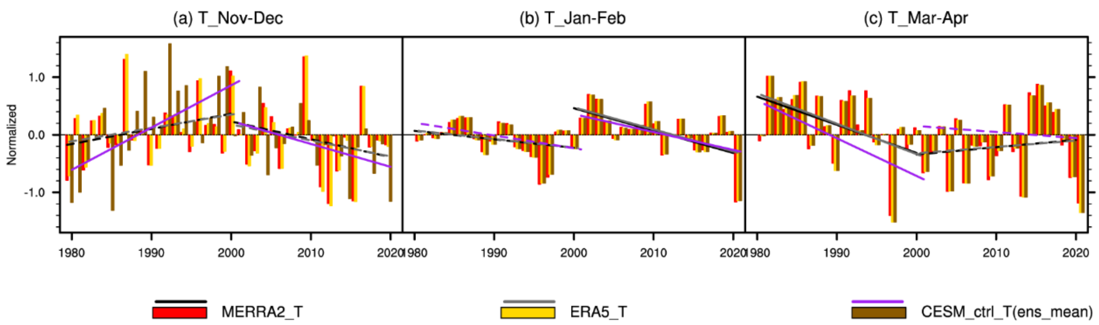

Figure R4. Same as Figure R3, but derived from the ensemble mean of the control experiments. This is Figure 2 in the revised manuscript.

Figure R5 shows the trends in daily temperature and ozone between 10 and 250 hPa in the polar cap regions (65°–90°N) during the pre-2000 period, which are based on data from MERRA-2 and the control experiments. Fig. R5c, R5d shows the results derived from the old control experiment in the original manuscript, while Fig. R5e, R5f shows the results of the ensemble mean of the control experiments. The trend reversal is also evident in December, which is consistent with Figs. R3 and R4. During November and December, there is an increasing trend in both temperature and ozone across all levels in the old control experiment (Fig. R5a, R5b). While after December, the trends in temperature and ozone reverse in the middle stratosphere and then in the lower stratosphere. Similar trend patterns are found in the old control experiment (Fig. R5c, R5d) and the ensemble control experiments (Fig. R5e, R5f), indicating that the ensemble control experiments can reproduce the long-term trends in stratospheric temperature and ozone in both early and late winter. In summary, the additional ensemble members do not affect the trends in Arctic stratospheric temperature.

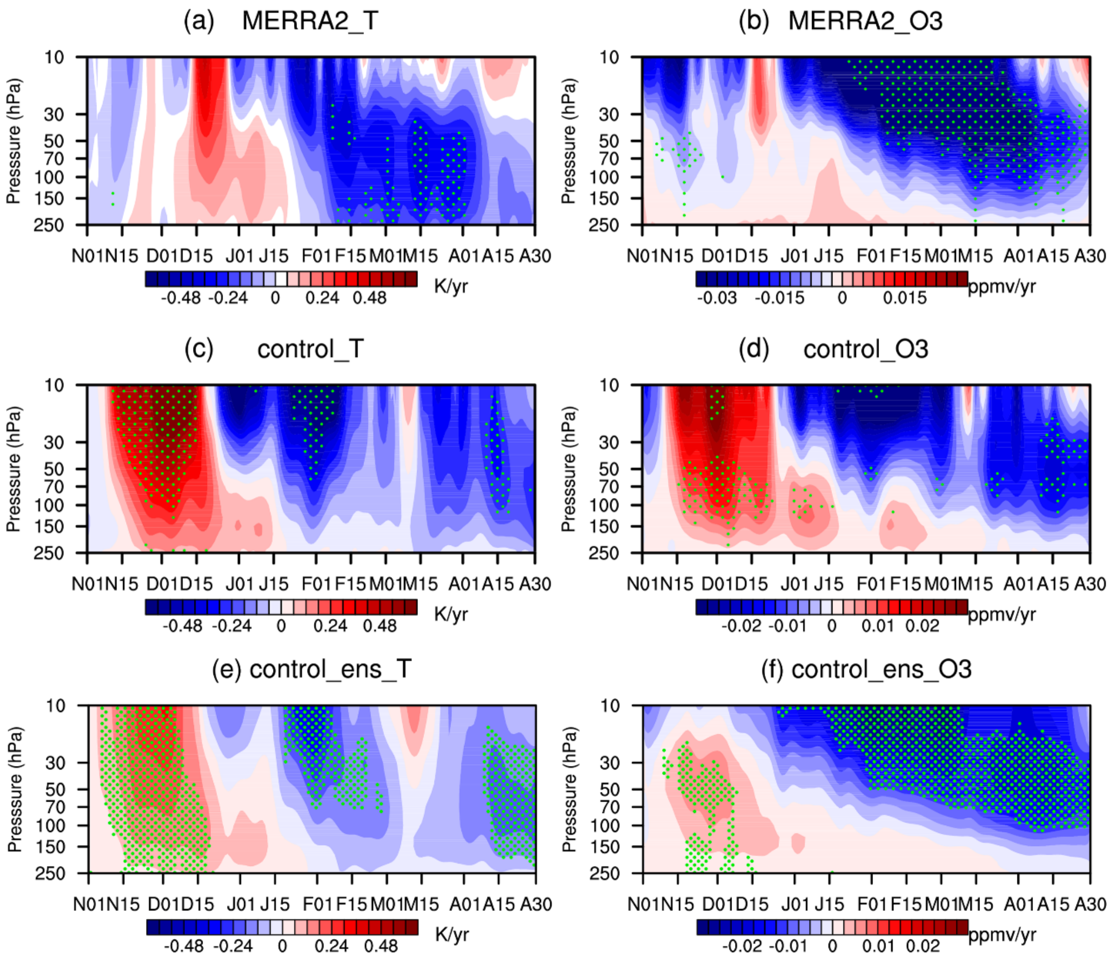

Figure R5. Time evolution of trends in daily temperature (a, c and e) and ozone (b, d and f) in the polar cap regions (65°–90°N) during winter and spring derived from MERRA2 (a, b), the one ensemble of control experiment (c, d) and the 5 ensemble mean of the control experiments (e, f) in the pre-2000 period. The green dotted regions indicate that the trends are statistically significant at the 90% confidence level according to Student's *t* test. This is Figure 3 in the original manuscript.

Figure R6a, R6b show the daily trends in temperature and ozone between 10 and 250 hPa in the polar cap regions (65°–90°N) before 2000 derived from the old O3clm experiment. The old O3clm experiment shows a nonsignificant temperature trend from November to December and a positive trend in late February and March. This result is opposite to those in the old control experiment (Fig. R5b, R5c). The stratospheric ozone exhibits negative trends over the 10–100

hPa from November to April, without an intra-seasonal reverse. The differences in trends of temperature and ozone between the old control experiment and old O3clm experiment are shown in Fig. R6c and R6d, which also shows an intra-seasonal reverse around December.

Figure R7a and R7b show similar trends to those in Figure R6a and R6b, except that the non-significant positive temperature trend from late February to early March became smaller and shorter in duration. The negative temperature trend in April is larger than those in the original manuscript but still insignificant. The ozone trend in the lower stratosphere is different from the previous results, as evidenced by a non-significant positive trend below 30 hPa in December and a negative ozone trend during January-April. It is worth noting that the ozone trend in late winter and spring derived from the new ensemble O3clm experiments still shows significant negative trends, which may be contributed by the chemical ozone depletion induced by increasing ODSs in the pre-2000 period (Fig. R7b). Conversely, the stratospheric ozone during February and early spring in the new O3clm experiment in the post-2000 period shows a significant positive trend (Fig. 13b in the revised manuscript), which is consistent with that in the old O3clm experiment in the original manuscript. This result suggests that the new O3clm experiment has excluded the potential impact of ozone decline as input field, which is the biggest concern of the reviewer #1. In addition, the difference in trends between the ensemble mean of the control and O3clm experiments is basically consistent with those in the original manuscript, except that the trend is smaller compared to the previous results, which is partially contributed by internal variability. These results indicate that the new control and new O3clm experiments with increased 5 ensemble members do not substantially affect the analysis results of the ozone-climate interaction feedbacks, although there is a weaker reduction in the strength of the trend in Arctic stratospheric temperature.

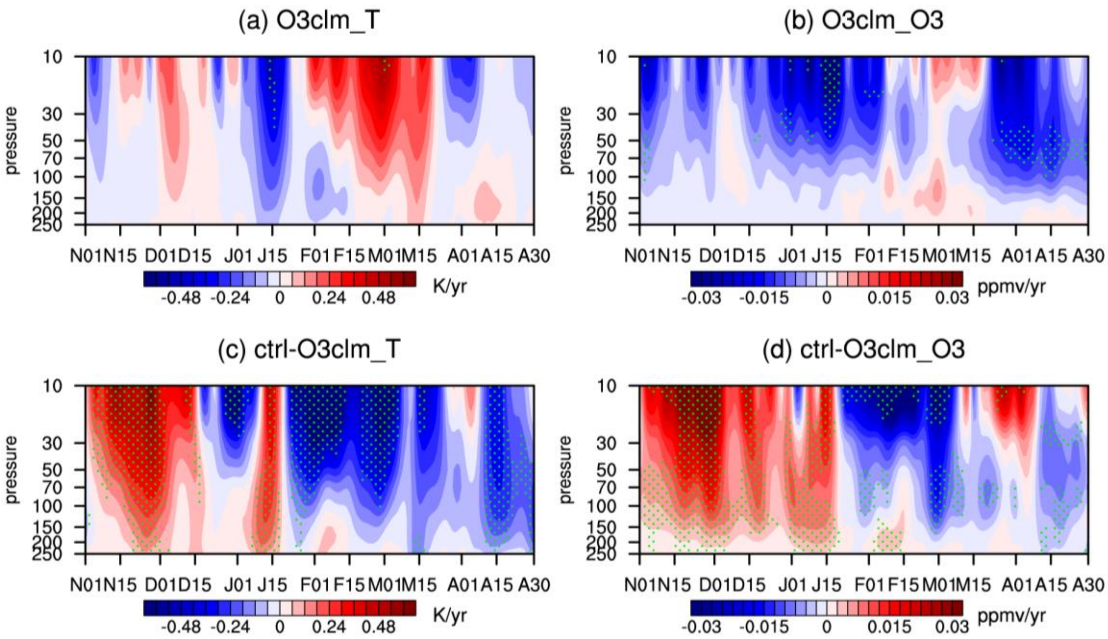

Figure R6. Time evolution of the trend of daily temperature and ozone over the levels between 10 and 250 hPa in the polar cap regions (65°–90°N) during winter and spring derived from the O3clm experiment (a–b) and the differences between the control experiment and O3clm experiment (c–d) before 2000. The green dotted regions indicate that the trend is statistically significant at the 90% confidence level according to Student's *t* test. This is Figure 4 in the original manuscript.

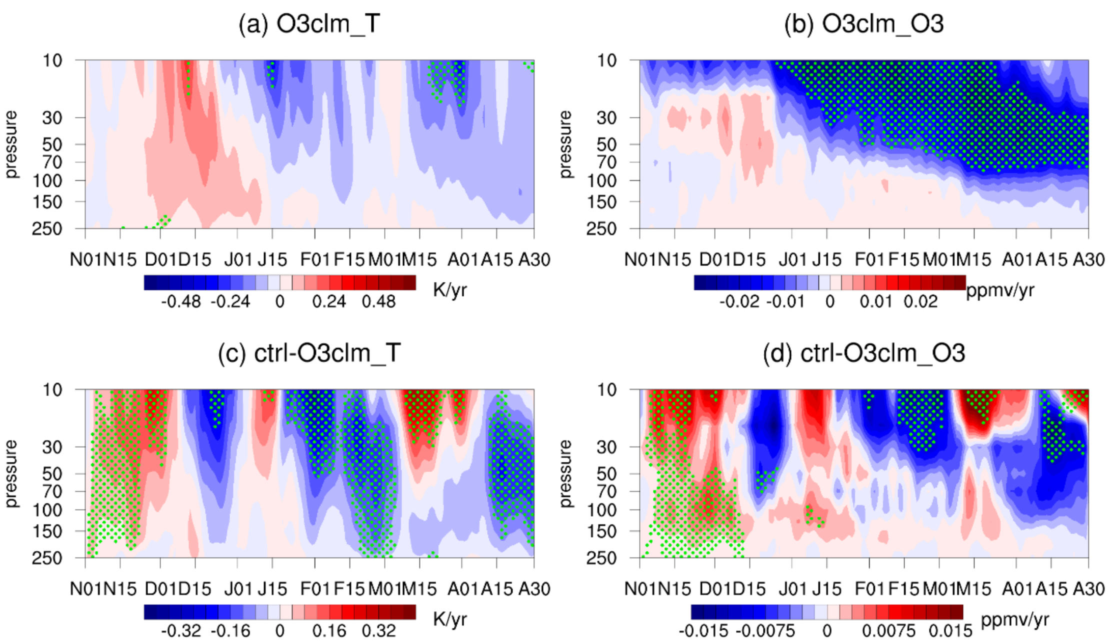

Figure R7. Same as Figure R6, but from the 5 ensemble mean of the O3clm

experiments and the difference between the ensemble mean of the control and O3clm experiments. This is Figure 4 in the revised manuscript.

The core process of ozone-climate interactions is ozone-circulation feedback. Figure R8 displays the trend in the vertical component downwelling branch of the BDC ($\overline{w}*$) averaged over the polar regions (65°–90°N) during the pre-2000 period in the ensemble control experiments and O3clm experiments. We decomposed these trends into contributions from wave 1 (Fig. R8b, e and h) and wave 2 (Fig. R8c, f and i). The ensemble mean of the control experiments shows significant negative trends in $\overline{w}*$ from November to early December, corresponding to enhanced downwelling compared to climatological mean, and positive trends in $\overline{w}*$ from late December to January, corresponding to weakened downwelling (Fig. R8a). After February, the trends in $\overline{w}*$ are less significant (Fig. R8a). The linear trends in $\overline{w}*$ are basically opposite to those in temperature derived from the ensemble control experiments (Fig. R5e), which is because the enhanced downwelling (upwelling) favors polar adiabatic warming (cooling). Additionally, the $\overline{w}*$ trend contributed by wave 1 is similar to the total trend, suggesting that wave 1 dominates the trends in $\overline{w}*$. In the ensemble O3clm experiments, there is no negative trend in $\overline{w}*$ in November and early December (Fig. R8d–f). This result indicates that ozone-circulation feedback strengthens the $\overline{w}*$ in early winter, leading to adiabatic warming in early winter; conversely, there are anomalous upward motions that induce anomalous adiabatic cooling from January to February, which is consistent with the reversal of the temperature trend in January (Figs. R5, R7). The difference between the ensemble control and O3clm experiments suggests a similar pattern to that of the ensemble control experiments (Fig. R8g, h and i). The results from the ensemble mean of the control

experiments, O3clm experiments and the difference between the ensemble mean of the two experiments are consistent with those from the old experiments, indicating that the Arctic stratospheric temperature trends are indeed driven by ozone-climate interactions rather than internal variability. Overall, the results of the new ensemble experiments still support the intra-seasonal reverse in the trend in Arctic stratospheric temperature around early winter.

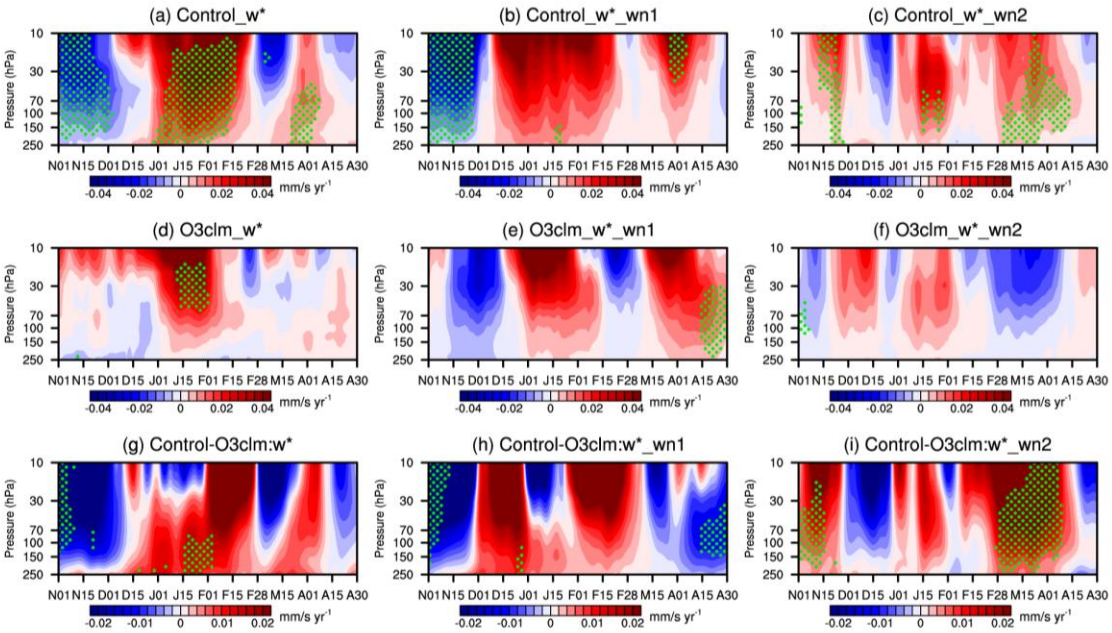

Figure R8. Linear trend of the vertical component ($\overline{w}*$) of the BDC and its contribution to the wavenumber 1 (b, e and h) and wavenumber 2 components (c, f and i) before 2000 averaged in the polar regions (65°–90°N) during winter and spring, derived from the ensemble control experiments (a, b and c), O3clm experiments (d, e and f) and the differences between the ensemble mean of the control and O3clm experiments (g, h and i). The green stippled regions indicate the trend in $\overline{w}*$ significant at the 90% confidence level according to Student's *t* test (The daily data are first processed with a 30-day low-pass filter to remove high-frequency signals). This is Figure 5 in the revised manuscript.

Our new experiments also support the finding in the original manuscript that

enhanced the downwelling of BDC trends associated with ozone-climate interactions can be attributed to the upward planetary waves. Figure R9 shows the trends in stratospheric planetary wave activity over the subpolar regions (50°–80°N) from November to April. In the ensemble control experiments, there is a significantly positive trend in the waves entering the stratosphere in November and early December before 2000, which is accompanied by intensified wave flux convergence in the middle and lower stratosphere (approximately 10–100 hPa; Fig. R9a). However, in late December and January, the waves entering the stratosphere decrease, accompanied by weakened wave flux divergence. These features imply that stratospheric planetary wave activity strengthened in November and early December and weakened in late December and January during the pre-2000 period, which is consistent with the findings of previous studies (Bohlinger et al., 2014; Young et al., 2012). In contrast, in the ensemble O3clm experiments, waves entering the stratosphere in November and early December decrease, and there is no significant convergence trend before 2000 (Fig. R9d). The trends in the planetary wave are mainly contributed by the wave 1 component rather than by wave 2 (Fig. R9b, c, h, and i). In November and early December, more propagation of planetary into the stratosphere weakens the circumpolar westerlies and increases the temperature in the Arctic lower stratosphere, which is consistent with the enhanced downward motions shown in Fig. R8. The trends in E-P flux and its convergence in January and February are opposite to those in early winter. Overall, the changes in upward wave propagation and BDC make a major contribution to reverse the stratospheric temperature trend at the intra-seasonal timescale during winter. It is worth noting that the planetary wave activity only changes noticeably before February in the ensemble mean of control experiments and O3clm experiments, and then gradually weakens in spring. This suggests that dynamic feedback processes induced by ozone-climate interactions mainly occur in winter. The results of the ensemble mean of experiments do not change the turnaround change in the trend in planetary wave.

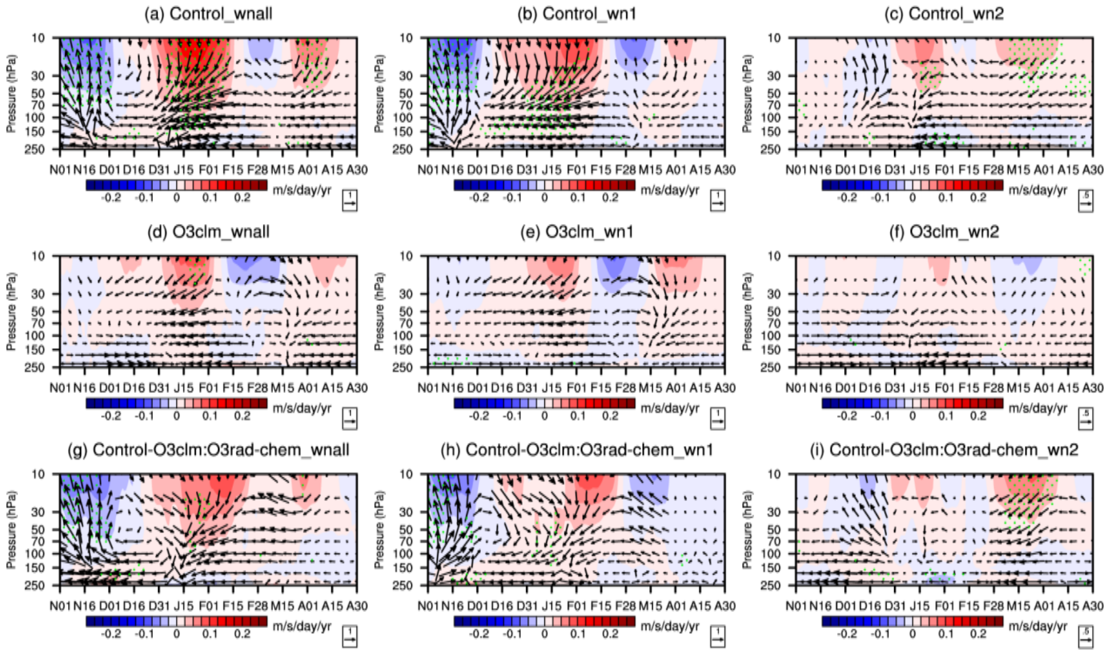

Figure R9. Trends in E-P flux (a, d and g; arrows; units of horizontal and vertical components are 10^4 and 10^2 kg s^{-2} yr^{-1}, respectively; an arrow pointing to the right indicates poleward propagation, whereas an arrow pointing to the left indicates equatorward propagation) and its divergence (shading) with their wave 1 components (b, e and h) and wave 2 components (c, f and i) over the levels between 10 and 250 hPa before 2000 averaged in the subpolar regions (50°–80°N) during winter and spring, as derived from the ensemble control experiments (a–c), O3clm experiments (d–f) and the differences between the ensemble mean of the control experiments and O3clm experiments (g–i). The green stippled regions indicate the trend in the E-P flux divergence significant at the 90% confidence level according to Student's *t* test (The daily data are first processed with a 30-day low-pass filter to remove high-frequency signals). This is Figure 7 in the revised manuscript.

Figure R10 shows the evolution of trends in shortwave heating rate (referred to as the QRS) and longwave heating rate (referred to as the QRL) from November to April in the two experiments. Both the ensemble control and O3clm experiments reveal small QRS trends from November to mid-February because sunlight cannot

reach the Arctic regions. In the ensemble control experiments, the QRL heating from November to early December shows a negative trend corresponding to the longwave cooling effect. In contrast, in the ensemble O3clm experiments, the ozone-climate interactions are removed and there is no significant QRL trend. The QRL cooling in the ensemble control runs occurs because a warmer air parcel corresponding to the positive temperature trend in early winter emits more longwave radiation and hence cools faster. After February, the upward propagation of planetary waves and ozone-circulation feedback processes weaken, whereas the contribution of shortwave radiative processes to stratospheric temperature increases as sunlight reaches the Arctic region. The ensemble control experiments demonstrate that the QRS shows a significant negative trend during the ozone-depletion period, which leads to a lower temperature and an strengthened polar vortex (Brasseur and Solomon, 2005). However, in the ensemble O3clm experiments, the radiative effects of ozone-climate interactions are inactivated, leading to insignificant changes in QRS throughout the entire winter and spring. This result further suggests that the design of the new O3clm experiment is credible.

In addition, negative temperature anomalies (Figs. R4c, R5c and R5e) emit less longwave radiation. The temperature then increases and generates positive QRL anomalies in spring. The differences in QRS and QRL trends between the ensemble mean of control and O3clm experiments exhibit nearly same patterns as those in the original manuscript. Our results demonstrate that the ozone-climate interactions during early winter mainly influence stratospheric temperature through dynamic adjustments. In contrast, the trends in temperature during late winter and spring are primarily due to dynamic cooling and shortwave cooling. Overall, the results of the ensemble mean of the two experiments do not change the trend of QRL and QRS, which is consistent with the original manuscript.

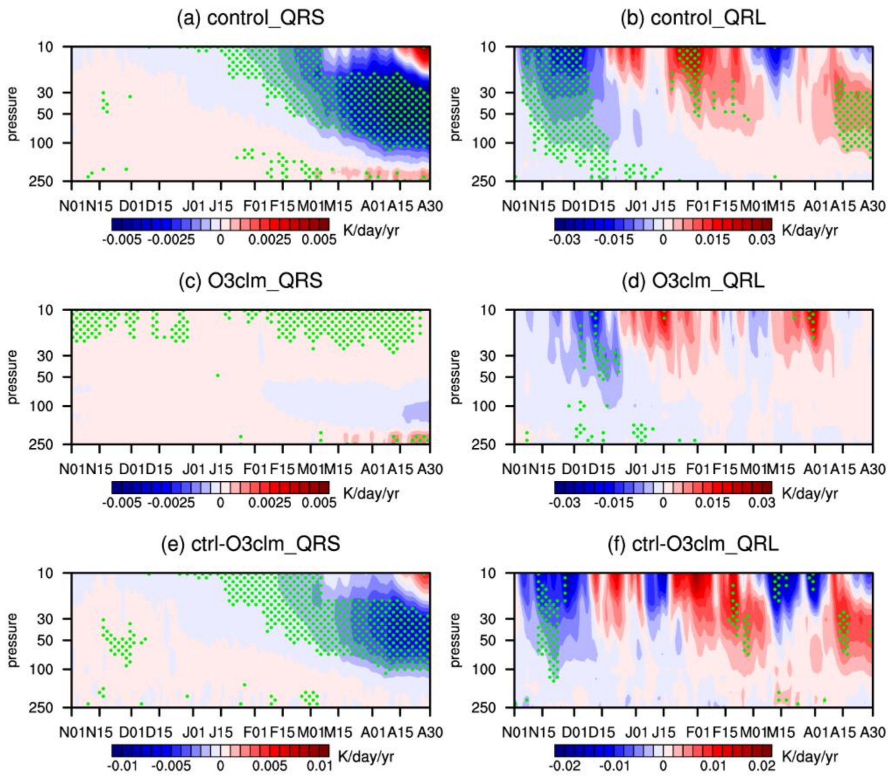

Figure R10. Time evolution of trends in the daily shortwave heating rate (solar heating rate; QRS) and longwave heating rate (QRL) between 10 and 250 hPa in the polar regions (65°–90°N) during winter and spring derived from the ensemble mean of the control experiments (a, b), O3clm experiments (c, d) and the difference between the two experiments (e, f) before 2000. The green dotted regions indicate that the trends are statistically significant at the 90% confidence level according to Student's *t* test (Nine-point smoothing was performed during drawing to remove noisy signals). This is Figure 11 in the revised manuscript.

In summary, the new ensemble mean of the control experiments, O3clm experiments and the difference between the two experiments are consistent with those in the original manuscript, and a detailed explanation of the mechanism is given in Section 4 of the revised manuscript. Although we use a new initial field for the ozone climate state in the O3clm experiment, the effect of the ozone-climate interaction does not change substantially, practically noted that there still exists an intra-seasonal temperature reversal around early winter. Therefore, we

conclude that the long-term trend in temperature and ozone is not affected by the initial field of the climate state. By redesigning the experiments and adding transient runs with 5 ensemble members, we have effectively addressed the issues raised by the reviewers and significantly improved the scientific validity and reliability of this study.

Other comments:

The introduction does not follow a clear outline. Sometimes it is unclear whether the authors are referring to interannual or long-term processes. The introduction reviews mostly literature that focuses on ozone-climate coupling on interannual timescales, but then the study focuses on long-term trends. Please tailor the introduction a bit better to the aim of this study. Some of the statements made in the introduction are also not supported by the cited literature (see detailed comments below). The title of the study is also misleading, as is suggests that this study focuses on interannual variability rather than long-term trends.

Response: We thank the reviewers for their constructive comments on the introduction and title of the manuscript. The title of the revised paper has been changed into "*Effects of Ozone-Climate Interactions on the Long-Term Temperature Trend in the Arctic Stratosphere*". Additionally, in order to better align the introduction with the long-term trends in stratospheric ozone and temperature, we have written the introduction and the following is the revised introduction (see lines 23-143):

"The stratospheric ozone layer plays an important role in global climate change (Son et al., 2008; Smith and Polvani, 2014; Xia et al., 2016; Xie et al., 2018; Hu et al., 2019a; Sigmond and Fyfe, 2014; Chiodo et al., 2021; Ivanciu et al., 2022; Friedel et al., 2023). Its absorption of solar ultraviolet (UV) radiation, along with its strong infrared radiation (IR) absorption and emission around the 9.6 μm band, is crucial for the Earth's energy balance and the thermal structure of the atmosphere (de F. Forster and Shine, 1997). The annual global mean radiative forcing of stratospheric

ozone during the strongest ozone depletion period (1979–1996) is relatively small (−0.22±0.03 W/m^2; de F. Forster and Shine, 1997) compared to that of CO_2 (2.16±0.25 W/m^2; IPCC, AR5, 2014). However, in addition to the direct radiative forcing mentioned above, stratospheric ozone can also significantly impact atmospheric temperature through the ozone-climate interactions, which involve chemical-radiative-dynamical coupling processes (Dietmüller et al., 2014; Nowack et al., 2015). For instance, neglecting interactive stratospheric chemistry and considering only ozone's direct radiative effect in climate models result in 20% overestimation of surface temperature in scenarios with the quadrupled CO_2 concentrations (Nowack et al., 2015). A similar overestimation of surface temperatures can also be found in the study of Chiodo and Polvani (2016). Additionally, Rieder et al. (2019) demonstrated that ozone-climate interactions are important for accurately capturing stratospheric temperature variability in models. However, some studies, such as Marsh et al. (2016), suggested that ozone-climate interactions have limited influences (approximately 1%) on climate sensitivity. Therefore, whether the ozone-climate interactions have significant influence on temperature variability is still unclear.

The ozone-climate interaction is complex, especially in the polar stratosphere. It involves different feedback mechanisms that vary across seasons. In winter, although solar radiation in the Arctic regions is absent, ozone can still absorb and emit longwave radiation. Seppälä et al. (2025) pointed out that a reduction in stratospheric ozone could directly lead to stratospheric warming. This longwave radiative warming may influence the strength of the Arctic polar vortex (Hu et al., 2015), further modulating the transport of ozone-rich air from mid-latitudes to the Arctic polar regions (Zhang et al., 2017). In addition, the Arctic ozone can modulate the planetary wave activity, which further influences Arctic stratospheric temperature via wave-mean flow interactions in winter (Nathan and Cordero, 2007; Albers and Nathan, 2013; Hu et al., 2015). Thus, Arctic stratospheric ozone affects stratospheric *temperatures through its longwave radiative effects and dynamical processes during winter. In late-February and early spring, as solar radiation reaches high latitudes, the polar regions become warm compared to winter and the stratospheric polar vortex is weakened. However, from the perspective of climate, the increase in ozone depleting substances (ODSs) in the 20th century leads to springtime stratospheric ozone depletion and decreased absorption of shortwave radiation, which cools the Arctic stratosphere and strengthens the polar vortex (Friedel et al., 2022a). This results in reduced wave propagation towards the lower stratosphere and thereby a colder Arctic stratosphere (Coy et al., 1997; Albers and Nathan, 2013; Haase and Matthes, 2019). On the one hand, the strengthened Arctic polar vortex decreases ozone transport to the polar regions, further reducing ozone concentrations. On the other hand, a colder Arctic stratosphere facilitates the formation of polar stratospheric clouds (PSCs). PSCs provide sites for heterogeneous reactions. The reactions convert stable chlorine reservoir species into active chlorine, then catalytically destroys ozone (Solomon et al., 1986; Feng et al., 2005a, 2005b; Calvo et al., 2015). Therefore, the ozone-climate interactions in winter and spring involve different and complex chemical-radiative-dynamical feedback processes, which operate on different timescales (Tian et al., 2023).*

The Arctic plays a crucial role in the global climate system, and its temperature changes have profound implications for global climate patterns (Cohen et al., 2014; Serreze and Barry, 2011; Overland et al., 2016). In recent decades, the Arctic long-term temperature trends are not only driven by a range of external factors such as sea ice, greenhouse gas emissions (GHG), and aerosols (IPCC, AR6, 2021; Shindell and Faluvegi, 2009; Screen and Simmonds, 2010), but also influenced by natural variability in the climate system. During the period from 1950 to 2000, in late-winter, a negative trend in stratospheric temperature is observed in the Arctic regions, which is associated with the weakening of wave activity (Randel et al., 2002; Zhou et al., 2001; Hu and Tung, 2003). On the other hand, the temperature trends in early and *mid-winter (November-January) are opposite to those in late winter from 1980 to 2000 (Bohlinger et al., 2014; Young et al., 2012). Most previous studies focused only on the role of dynamical processes in the seasonal difference in temperature trends (Newman et al., 2001; Hu and Fu, 2009; Young et al., 2012; Ossó et al., 2015; Fu et al., 2019). However, these long-term trends in Arctic temperatures are not fully explained by dynamical processes. A recent work by Chiodo et al. (2023) has explored the impact of long-term ozone trends on the temperature in the Arctic, providing valuable insights into the ozone-climate interactions. Notably, the Arctic ozone layer has also undergone significant changes over the past 40 years (WMO, 2018). The ozone layer experienced significant depletion after the Industrial Revolution (Farman et al., 1985) and has been recovering slowly in the 21st century as ODSs is decreased (WMO, 2018; Newman et al., 2007; Chipperfield et al., 2017). Additionally, the influence of ozone-climate interactions on temperature in polar regions differs across seasons (Tian et al., 2023). Therefore, it is worth investigating whether Arctic ozone trends and their climate interactions can explain the long-term trends in Arctic temperature across different seasons.*

This study focuses on the historical long-term trends in the Arctic stratospheric temperature during winter and spring, with a particular emphasis on the role of ozone-climate interactions. Specifically, we seek to answer the following questions: (1) What are the observed trends in Arctic stratospheric temperature and ozone concentrations over recent decades? (2) How do ozone-climate interactions contribute to these trends? (3) What mechanisms drive the seasonal differences in these trends? By addressing these questions, this study aims to enhance our understanding of the role of ozone-climate interactions in long-term Arctic stratospheric changes and their implications for future climate projections. Section 2 outlines the data, methodologies, and climate model experimental designs employed in this study. Section 3 presents the observed trends in temperature and ozone concentrations over the Arctic stratosphere, and Section 4 explores the underlying

***physical processes. Finally, section 5 summarizes the conclusions and discusses future directions.*"**

Line 8: "increased"

Response: Corrected, thank you.

Line 15: "cooling trends in the Arctic stratosphere are ..."

Response: Corrected, thank you.

Line 35: Please be a bit more precise here. Marsh et al. (2016) conclude that ozone feedbacks are not crucial for the model's climate sensitivity in 4xCO2 forcing experiments. Maybe it is worth citing Rieder et al. (2019) in this context, who showed that ozone variations are important for the stratospheric temperature variability in models.

Response: Thank you for your suggestion. We revised the text and provided additional context on the importance of ozone variations. The revised manuscript as follows (see lines 37-43):

"*Additionally, Rieder et al. (2019) demonstrated that ozone-climate interactions are important for accurately capturing stratospheric temperature variability in models. However, some studies, such as Marsh et al. (2016), suggested that ozone-climate interactions have limited influences (approximately 1%) on climate sensitivity.*"

Lines 44: I could not find any evidence for this statement (i.e. the longwave ozone effect on stratospheric dynamics during winter) in the cited study (Strahan et al., 2013). Could you please provide further literature on the mid-winter longwave radiative effect of ozone?

Response: We appreciate the reviewer pointing out this oversight. The revised sentence will read (see lines 47-61):

“***In winter, although solar radiation in the Arctic regions is absent, ozone can still absorb and emit longwave radiation. Seppälä et al. (2025) pointed out that a reduction in stratospheric ozone could directly lead to stratospheric warming. This longwave radiative warming may influence the strength of the Arctic polar vortex (Hu et al., 2015), further modulating the transport of ozone-rich air from mid-latitudes to the Arctic polar regions (Zhang et al., 2017). In addition, the Arctic ozone can modulate the planetary wave activity, which further influences Arctic stratospheric temperature via wave-mean flow interactions in winter (Nathan and Cordero, 2007; Albers and Nathan, 2013; Hu et al., 2015). Thus, Arctic stratospheric ozone affects stratospheric temperatures through its longwave radiative effects and dynamical processes during winter.***”

Lines 47: Are you now talking about mid- or late-winter/spring? I believe this statement is only valid for springtime, when the polar vortex is already weakened. See also Haase and Matthes (2019).

Response: Thank you for highlighting this point. To address this, we revise the text for clarity and include a reference of Haase and Matthes (2019). The revised sentence is specified as (see lines 61-75):

“***In late-February and early spring, as solar radiation reaches high latitudes, the polar regions become warm compared to winter and the stratospheric polar vortex is weakened. However, from the perspective of climate, the increase in ozone depleting substances (ODSs) in the 20th century leads to springtime stratospheric ozone depletion and decreased absorption of shortwave radiation, which cools the Arctic stratosphere and strengthens the polar vortex (Friedel et al., 2022a). This results in reduced wave propagation towards the lower stratosphere and thereby a colder Arctic stratosphere (Coy et al., 1997; Albers and Nathan, 2013; Haase and Matthes, 2019). On the one hand, the strengthened Arctic polar vortex decreases ozone transport to the polar regions, further reducing ozone concentrations. On the other hand, a colder Arctic stratosphere facilitates the formation of polar stratospheric clouds (PSCs).***

PSCs provide sites for heterogeneous reactions. The reactions convert stable chlorine reservoir species into active chlorine, then catalytically destroys ozone (Solomon et al., 1986; Feng et al., 2005a, 2005b; Calvo et al., 2015).**"**

Line 85: I do not really understand this sentence (starting with "Lin et al. ... "). Could you please reformulate?

Response: In the revised manuscript we reorganized the introduction to focus more on the long-term trends in Arctic stratospheric temperature and the deletion of this sentence.

Lines 91 : Chiodo et al. (2023) studied the impact of long-term ozone trends in the Arctic on temperature and dynamics. Might be worth mentioning this here.

Response: Thank you for your comment. We have rephrased as follows (see lines 126-127):

"*A recent work by Chiodo et al. (2023) has explored the impact of long-term ozone trends on the temperature in the Arctic, providing valuable insights into the ozone-climate interactions.*"

(9)Lines 94 . "..., we focus on the historical long-term trends ..."

Response: Corrected, thank you.

Lines 202: To support this statement on the persistent cooling, you would have to calculate a trend over the whole time period. When doing this, you would probably get no trend, e.g. no significant temperature changes from 1980-2020.

Response: Thank you for your attention to detail. There is no evidence of sustained cooling, so we modified the expression as follows (see lines 280-282):

"*From January to February, the temperature displays an insignificant negative trend*

***before 2000 and a significant negative trend after 2000, derived from the three datasets (Fig. 2b).*"**

Fig. 2: How have the time series been normalised?

Response: In this study, the normalized time series are standardized using Z-score standardization, where the data are processed using the following formula: $A_{s\text{-}value} = \frac{A_{o\text{-}value} - \bar{A}}{\sigma_A}$, where $A_{s-value}$ denotes the normalized A-value, $A_{o-value}$ denotes original A-value, $\bar{A}$ denotes average A-value, σ_A denotes standard deviation. This method transforms the data into a distribution with a mean of 0 and a standard deviation of 1, making different datasets comparable. Using the Z-score standardization method can better compare trends across different datasets. We added the normalized method information in the section Method and please see lines 231-233.

The trends in Fig. 2 look a bit constructed, i.e. they seem to be very sensitive to the time chosen time frame. Especially the trends in springtime (March/April) seem to be entirely caused by the ozone depletion event in 1997.

Response: Thank you for your comment. To rule out the excessive impact of the year 1997, we recalculated the long-term trend by excluding the 1997 data from the calculation of the 2000 trend in Figure R11. The results show that the temperature and ozone trends during the pre-2000 period are not affected by the extreme ozone depletion event, and including 1997 does not change the negative springtime temperature and ozone trends (Fig. R3).

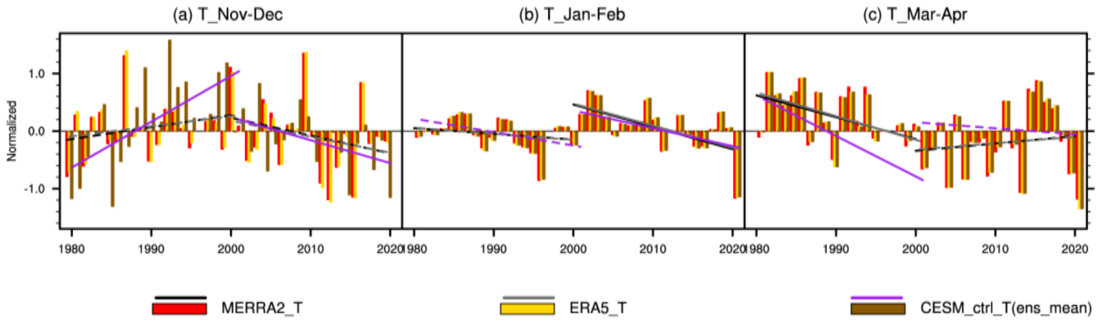

Figure R11. Normalized time series of the temperature averaged from 150 to 10 hPa over 65°–90°N from 1980–2020 in (a) November–December, (b) January–February, and (c) March–April derived from MERRA2 (red column), ERA5 (orange column) and CESM (brown column) the ensemble control experiments. The color straight lines represent the linear trends before 2000, which excludes data for 1997, and after 2000. Solid lines indicate that the trends are statistically significant at the 90% confidence level according to Student's *t* test.

In addition, the selection of 2000 is based on several scientific considerations: (1) Several studies provide evidence for a turning point in long-term stratospheric trends around the year 2000. Satellite observations from TOMS, OMI, and GOME reveal a turnaround in stratospheric ozone trends around 2000, with stabilization and signs of recovery (WMO, 2018; LOTUS, 2019). Ozonesonde measurements clearly indicate increased lower stratospheric ozone levels after 2000 corroborating satellite findings (IPCC, AR5, 2013). Perlwitz et al. (2008) indicated that the modeled climate response to ozone recovery is almost opposite to that of ozone depletion before 2000. These evidences point to a consensus on the year 2000 as a turning point in ozone depletion and recovery. (2) By dividing the analysis into two periods, pre- and post-2000, we can better isolate the different impacts of ozone depletion and recovery on Arctic stratospheric temperature and dynamics. While it is true that the turning point around 2000 may affect the significance of the trends, this effect is precisely one of the focuses of our study. By comparing trends before and after 2000, we aim to better understand how ozone-climate interactions evolve during the ozone depletion and recovery period.

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Response to Comments of Li Feng

The Arctic lower stratosphere experienced a warming trend in early winter but a cooling trend in late winter/early spring during 1980-1999. During the same period, the Arctic lower stratospheric ozone increased in early winter and decreased in late winter. This paper investigates the effects of stratospheric ozone changes on Arctic lower stratospheric temperature trends using CESM simulations and reanalysis. It is found that the early winter Arctic lower stratospheric warming was caused by enhanced dynamical warming, which was strongly modulated by the increase of Arctic ozone. In late winter/early spring, Arctic ozone depletion reduces shortwave heating and causes lower stratospheric cooling.

Overall, the paper is well written. The results can improve our understanding of how Arctic ozone change affects climate, which has received less attention. However, I have some major concerns about the analysis and I think a major revision is needed.

Response: We sincerely appreciate your thorough feedback and valuable suggestions. In response to Reviewer #1 and your comments, we have incorporated comprehensive new experiments, expanded discussions, and enhanced physical interpretations throughout relevant sections of the manuscript. These substantive revisions aim to strengthen the theoretical framework and improve the manuscript's clarity and scientific validity. We apologize for the extended review cycle due to the high computation costs of the ensemble experiments for control and O3clm experiments.

Major comment #1:

The authors have done a detailed analysis of how Arctic stratospheric ozone changes affect the circulation, but they do not investigate how circulation changes affect Arctic ozone. For example, ozone increase in early winter leads to stronger wave propagation into the stratosphere and Arctic warming. They should also consider the effects of an enhanced BDC on Arctic ozone increase. Indeed, the increasing ozone trend in early winter must be driven by dynamics.

Response: We sincerely thank the reviewers for their thorough review and valuable feedback. We agree with the reviewers that it is important to examine how circulation changes affect Arctic stratospheric ozone's trend. Especially, whether the enhanced wave propagation and the Brewer-Dobson Circulation (BDC) drive early winter ozone trends. We provide a detailed response to the comment and outline revisions made to address the issue.

Previous studies used Transformed Eulerian Mean (TEM) equation combined with zonal-mean ozone tracer continuity equation to diagnose the ozone transport induced by the Brewer-Dobson circulation (BDC) and ozone eddy transport (Monier and Weare, 2011; Abalos et al., 2013; Zhang et al., 2017). The ozone budget equations are represented as follows (Monier and Weare 2011; Abalos et al. 2013):

$$\begin{aligned}\frac{\partial \overline{\chi_{O_3}}}{\partial t} = & \frac{\bar{v}^*}{R}\frac{\partial \overline{\chi_{O_3}}}{\partial \phi} - \bar{w}^*\frac{\partial \overline{\chi_{O_3}}}{\partial z} (term1) \\ & -\frac{1}{\rho_0}\nabla \cdot M \ (term2) \qquad \textbf{(Eq.1)} \\ & +\bar{S} \ (term3)\end{aligned}$$

where $\bar{S}$ is the sum of all chemical sources and sinks, $\bar{\chi}_{O_3}$ is the zonal-mean ozone concentration, $\bar{v}^*$ and $\bar{w}^*$ are the meridional and vertical BDC velocities (Andrews et al. 1987), respectively; M is the eddy flux vector, which is represented as:

$$\left[\rho_0\left(\overline{v'\chi'_{O_3}} - \frac{\overline{v'\theta'}}{\bar{\theta}_z}\frac{\partial \overline{\chi_{O_3}}}{\partial z}\right), \rho_0\left(\overline{w'\chi'_{O_3}} + \frac{1}{R}\frac{\overline{v'\theta'}}{\bar{\theta}_z}\frac{\partial \overline{\chi_{O_3}}}{\partial \phi}\right)\right], \quad \textbf{(Eq.2)}$$

$\nabla \cdot M$ is the divergence of the eddy flux vector and represents the eddy transport of ozone; ρ_0 is air density; θ is potential temperature; R is Earth's radius; t is time; ϕ and z are latitude and height, respectively.

Figure R1 shows the trend in stratospheric ozone budget from November to February between 10 and 250 hPa in the polar regions (65°–90°N) in the pre-2000 period, which is decomposed into BDC and eddy transport of ozone (term1 and term2 in Eqs. (1)). In the ensemble control experiments, from November to December (early winter), the total ozone budget shows a significantly positive trend, indicating an increase in ozone concentrations. This trend is primarily driven by the sum of BDC and eddy transport. In mid-winter, the trend in ozone budget weakens and changes to negative, indicating a leveling off of increased ozone concentration. In contrast, in the ensemble O3clm experiments, the trend in the ozone budget is opposite to those in the ensemble control experiments and is not statistically significant from November to February. This demonstrates that during early winter, the accelerated BDC intensifies poleward ozone advection through directly transports ozone-rich air masses from tropical reservoirs to polar region, and enhances downward transport of ozone from the upper stratosphere to lower stratosphere. The transport of ozone due to ozone-circulation feedback is reconfirmed by the difference between the ensemble mean of the control and O3clm experiments. In January, the difference between the two experiments shows an intra-seasonal reverse in ozone transport, indicating that the ozone-circulation interactions can also give feedback to ozone concentrations.

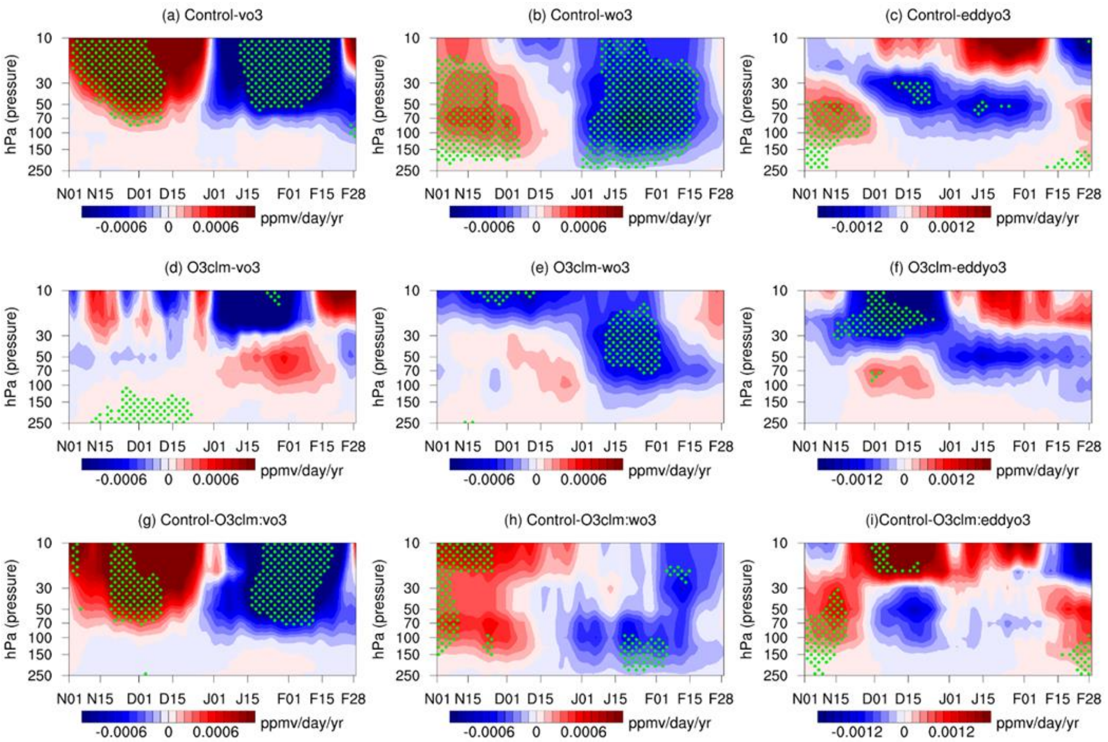

Figure R1. Dynamically produced ozone concentration trend, decomposed into (a, d and g) meridional and (b, e and h) vertical BDC transport and (c, f and i) eddy transport between 10–150 hPa in the polar regions (65°–90°N) from November to February, derived from (a–c) the ensemble control, (d–f) the O3clm experiments and (g–i) the difference between the two experiments during the pre-2000 period. The trend over the dotted regions is statistically significant at the 90% confidence level according to the Student's *t* test (The daily data are first processed with a 30-day low-pass filter to remove high-frequency signals).

The abovementioned analysis has been added in the revised paper and please see lines 375-397 and Figure 6 in the revised manuscript.

Major comment #2:

Line 315-317. This is a key result of this study. Note that Arctic lower stratospheric ozone has an increasing trend in Nov-Dec in the control experiment (Fig. 3d). Please explain how ozone increase (or ozone-circulation interactions) leads to a reversal of the refractive index from November to December.

Response: Thanks a lot for your comments. Nathan and Cordero (2007) pointed that wave-induced ozone heating decrease wave drag by about 25% in the lower stratosphere, favoring planetary wave propagation at this altitude during early winter in the present study (Figure R2; Figure 7a, g in the revised manuscript). Additionally, they pointed out that photochemically accelerated cooling due to ozone augments the Newtonian cooling and increases the wave drag by a factor of two in the upper stratosphere, which is in accordance with our finding that ozone-climate interactions enhance the upper stratospheric E-P flux convergence (Figure 7a, g in the revised manuscript). These analysis results highlight how ozone-climate interactions affect stratospheric dynamics processes.

Here we used wave refractive index (RI) change to analyze the influence of ozone-climate interactions on wave propagation. RI is used to diagnose the environment of wave propagation (Chen and Robinson, 1992) and is calculated as:

$$RI = \frac{\bar{q}_\varphi}{\bar{u}} - \left(\frac{k}{a\cos\varphi}\right)^2 - \left(\frac{f}{2NH}\right)^2 \quad \textbf{(Eq.3)}$$

where the meridional gradient of the zonal mean potential vorticity is calculated as:

$$\bar{q}_\varphi = \frac{2\Omega}{a}\cos\varphi - \frac{1}{a^2}\left[\frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}\right]_\varphi - \frac{f^2}{\rho_0}\left(\rho_0\frac{\bar{u}_z}{N^2}\right)_z \qquad \textbf{(Eq.4)}$$

where $-\frac{f^2}{\rho_0}\left(\rho_0\frac{\overline{u_z}}{N^2}\right)_z = \left(\frac{f^2}{HN^2} + \frac{f^2}{N^4}\frac{\mathrm{d}N^2}{\mathrm{d}z}\right)\overline{u_z} - \frac{f^2}{N^2}\overline{u_{zz}}$ **, and** $H, q, k, N^2, \Omega, u_z$ **are the scale height, potential vorticity, zonal wavenumber, buoyancy frequency, Earth's angular frequency, and zonal wind shear, respectively. Note that the second term of RI does not change with atmospheric state, which is always positive, and the third term of RI is insignificant compared to the first term. The second**

term is also insignificant for planetary waves with very small wave numbers (Hu et al., 2019). Previous studies indicate that changes in zonal mean potential vorticity meridional gradient $\bar{q}_{\varphi}$ could explain the most of changes in RI in the middle and high latitudes (e.g., Hu et al., 2019; Simpson et al., 2009).

Figure R2 shows the daily evolution of the trend in the RI, the vertical component of the E-P flux (F_z)and $\bar{q}_{\varphi}$ averaged between 45°–75°N and U60 (zonal wind at 60°N) in the lower stratosphere (50–150 hPa) before 2000. The datasets are derived from the ensemble control experiments and O3clm experiments. Specifically, in the ensemble control experiments, positive zonal wind vertical shear anomalies (Fig. R5) at middle latitudes during November increase the $\bar{q}_{\varphi}$ (Fig. R3), which in turn raises the RI and enhances the F_z (Fig. R2; purple lines). The increase in planetary waves in early winter weakens the polar vortex compared to that in the O3clm experiment, leading to deceleration in circumpolar westerlies during mid-December and January (red lines in Fig. R2). The decreased zonal wind around 60°N further suppresses the vertical propagation of planetary wave in the subsequent winter months, corresponding to the intra-seasonal reversal of F_z before and after January. Then, the weakening of F_z in the ensemble control experiments allows for a stronger recovery of the polar vortex due to wave-flow interaction in February compared to the O3clm experiments (red lines in Fig. R2). This intra-seasonal reversal of F_z explains the reversals of BDC and temperature around December, and this feature disappears in the ensemble O3clm experiments in which the ozone-interactions are cut off, highlighting the key role of ozone-climate interactions in modulating stratospheric dynamics processes. We have added the above-mentioned results in the revised manuscript (Please see lines 468-484 and Figure 8).

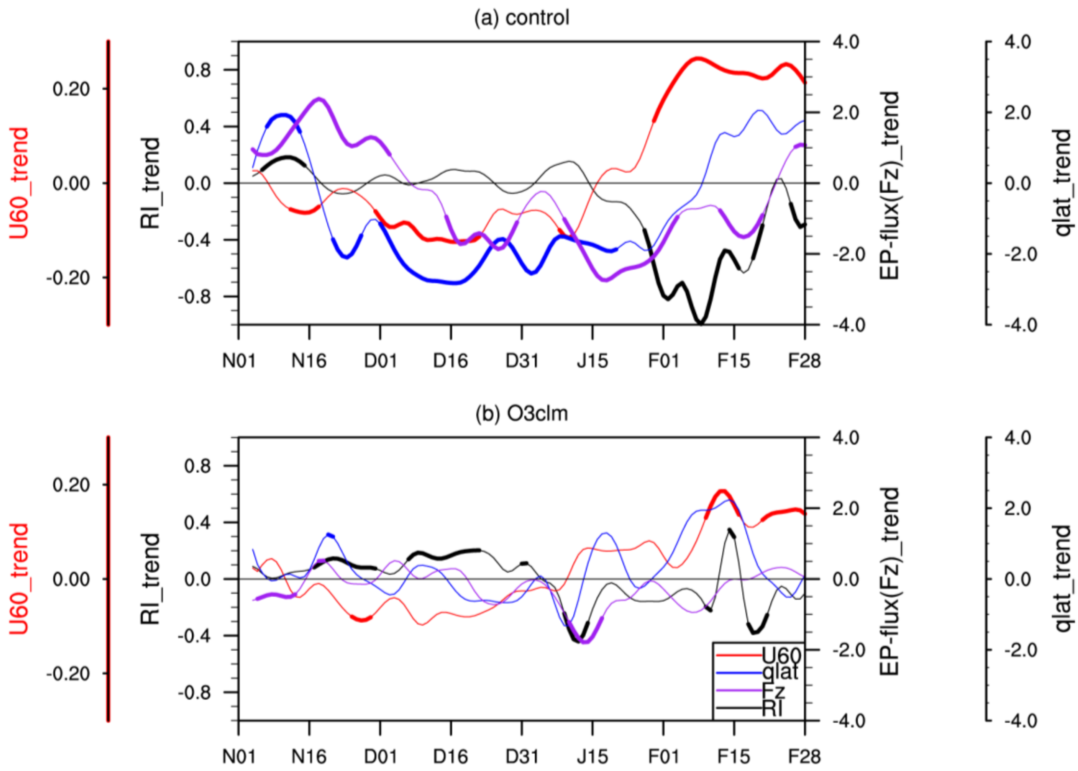

Figure R2. Daily evolution of the trends in the RI (black lines), vertical component of the E-P flux (F_z; purple lines), $\bar{q}_\varphi$ (blue lines), U60 (zonal wind at 60°N; red lines) before 2000 at 50–150 hPa averaged in mid-latitude (45°–75° N) from 1 November to 28 February, derived from (a) the ensemble mean of the control experiments and (b) O3clm experiments. The solid lines indicate the trends in the significant RI, vertical component of the E-P flux and $\bar{q}_\varphi$ at the 90% confidence level according to Student's *t* test (The daily data are first processed with a 7-day low-pass filter to remove high-frequency signals).

We further analyzed which term dominates the change in $\bar{q}_\varphi$. Figure R3 shows the pattern of the difference in $\bar{q}_\varphi$ between the high ozone period (1980−1985) and the low ozone period (1997−2002). According to the Eq. (4), the first term of $\bar{q}_\varphi$ does not change with the atmospheric state. Therefore, the second term

$(-[\frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}]_\varphi$; hereafter referred to as the Uyy term or barotropic term) and the third term ($-\frac{f^2}{\rho_0}(\rho_0\frac{\bar{u}_z}{N^2})_z$; hereafter referred to as the Uzz term or baroclinic term) are investigated. In the ensemble control experiments, the pattern of responses in the Uzz term is similar with $\bar{q}_\varphi$ (Figs. R3, R5). This implies that changes in $\bar{q}_\varphi$ over the Arctic in the stratosphere are mainly due to the Uzz term. The baroclinic term plays a dominant role in modulating the $\bar{q}_\varphi$ in the Arctic stratosphere. Similar results were obtained in a study from Hu et al. (2022). A reversal of $\bar{q}_\varphi$ in the upper troposphere and lower stratosphere (UTLS) over 60–70°N (Fig. R3a) leads to a reversal of the $\bar{q}_\varphi$ and RI from November to December. In the ensemble O3clm experiments, there is no significant $\bar{q}_\varphi$ increase in the UTLS region in November, nor did the baroclinic term provide favorable conditions (Fig. R5d). This suggests that ozone-climate interaction promotes planetary wave upward by affecting the baroclinic term, which in turn induces an increase in RI.

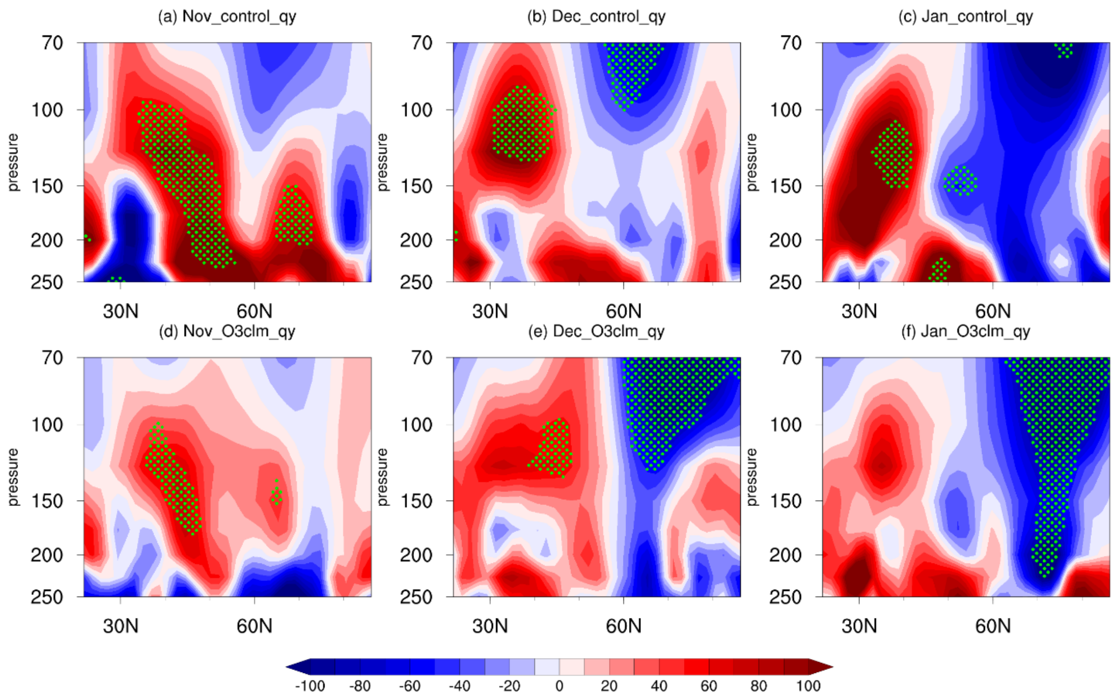

Figure R3. Altitude-latitude cross-section of difference in $a^2 \cdot \bar{q}_\varphi$ between the high

ozone period (1980−1985) and the low ozone period (1997−2002), derived from the ensemble control experiments (a, b and c) and O3clm experiments (d, e and f). Green dots indicate that the differences are statistically significant at the 90% confidence level according to Student's *t*-test.

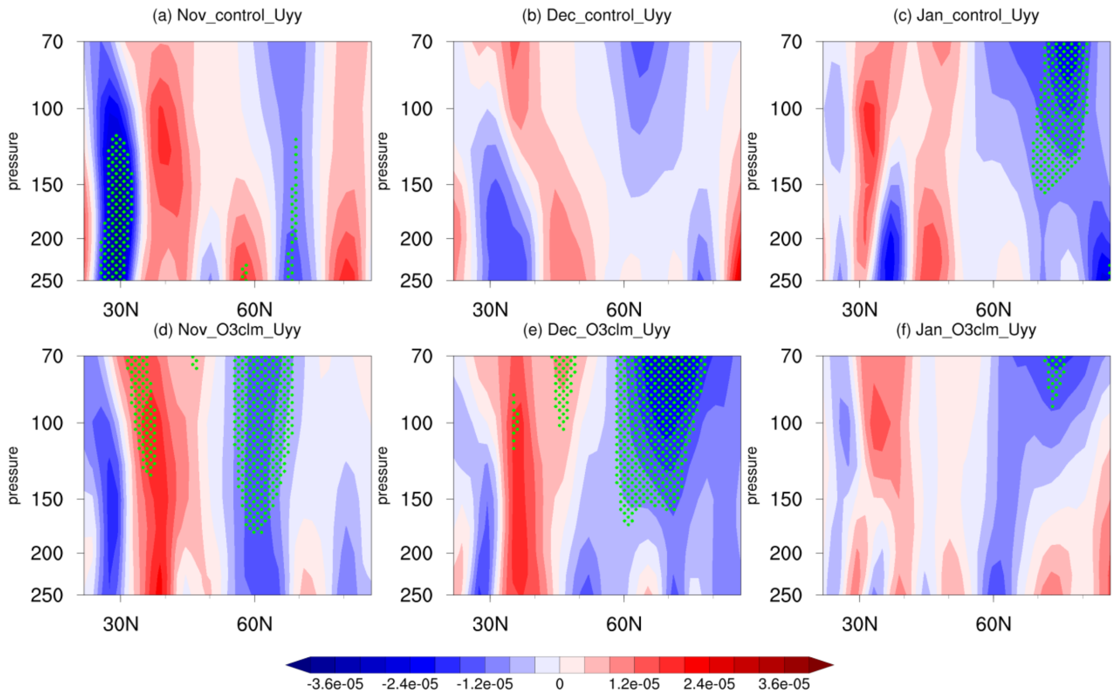

Figure R4. Same as Figure R3, but for the $-[\frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}]_\varphi$ **(U_{yy} term or barotropic).**

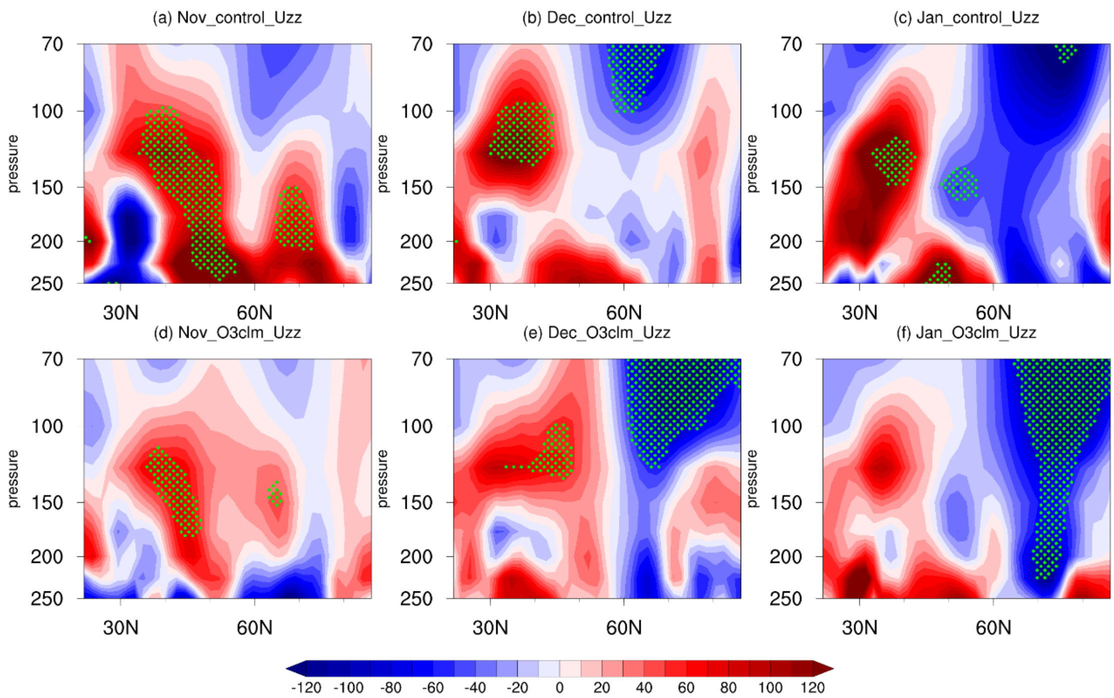

Figure R5. Same as Figure R3, but for the $-a^2 \cdot \frac{f^2}{\rho_0}(\rho_0 \frac{\bar{u}_z}{N^2})_z$ (U_{zz} term or baroclinic).

Minor Comments:

Lines 9-12: The paper does not show any result of ozone-induced longwave cooling. So, it should not be included in the abstract.

Response: Thank you for your comment. Actually, in our previous manuscript, Fig. 11f shows the result of ozone-induced longwave cooling. We described in detail the changes in longwave cooling induced by ozone and its effect on temperature in the main text (Figure 11 and lines 544-569 in the revised manuscript).

Line 15: "enhanced shortwave radiative cooling" --- reduced shortwave radiation warming

Response: Thank you for pointing this out. We rectified this expression in the revised manuscript, as detailed in lines 14-16:

"*In contrast, during late winter and spring, cooling trends in the Arctic stratosphere are predominantly driven by the reduced shortwave radiation heating associated with stratospheric ozone depletion.*"

Line 180: Is there only one member for each experiment?

Response: Thank you for your comments. In the original manuscript, each experiment includes only one ensemble member. We acknowledge that having more ensemble members would improve the reliability of the results by averaging out random interannual variability. Therefore, in the revised manuscript, we used five ensemble members both in control experiment and O3clm experiment to

reduce the experimental uncertainties. The analysis of new results derived from ensemble experiments can be found in Main comment #2 of the reviewer 1.

Lines 190-193: I wonder why you want to calculate ozone interactively in the O3clm experiment since the calculated ozone is not used in radiation. Why not just prescribe ozone?

Response: Thanks for your comment. The decision to calculate ozone interactively in the O3clm experiment, even though it is not used in the radiation scheme, is motivated by the need to maintain consistency in the model's chemical and dynamical processes. By allowing the ozone to be calculated interactively, the model ensures that the chemical processes involving ozone (such as its production and destruction) are consistent with the rest of the atmospheric chemistry. This is important because ozone interacts with other chemical species, and these interactions can influence the overall atmospheric state. Previous studies suggested that climate models without chemical-radiative-dynamical feedback process cannot capture the realistic variability of stratospheric compositions and other stratospheric processes (Cionni et al., 2011; Eyring et al., 2013; Jones et al., 2011). In addition, prescribing ozone might introduce biases in the model, especially if the prescribed ozone fields do not perfectly match the model's internal state. By calculating ozone interactively, the model avoids potential discrepancies that could arise from using prescribed fields, ensuring a more self-consistent simulation. Notably, the primary goal of the O3clm experiment is to isolate the effects of ozone-climate interactions by comparing it with the control experiment where ozone is fully interactive, especially for the chemical-radiative-dynamical processes induced by long-term ozone changes, which is our main point of innovation.

Lines 209-211: Move the two sentences to the beginning of the paragraph.

Response: Corrected, thank you.

Line 220: What causes the lower stratospheric ozone increase in Nov-Dec?

Response: The increase in lower stratospheric ozone during November–December is primarily driven by dynamical processes. Specifically, the enhanced ozone transport is induced by the BDC and eddy transport. Key contributing factors as follows: (1) Enhanced ozone transport by the BDC: In early winter, planetary wave activity leads to increased upward and poleward transport of ozone-rich air from the tropics into the Arctic lower stratosphere. This dynamical transport is particularly pronounced during years with strong wave driving, which accelerates the BDC's downwelling branch and leads to ozone accumulation in the Arctic lower stratosphere. (2) Ozone eddy transport: Eddy transport of ozone transports ozone-rich air into the Arctic lower stratosphere. (3) Suppressed ozone loss: During early winter, an absent of solar radiation levels reduce the activation of catalytic ozone-destroying reactions involving halogens. This radiative condition allows transported ozone to accumulate with minimal chemical loss. The updated text as follows (see lines 375-397):

"*Furthermore, the enhanced BDC may have an effect on the ozone concentration. The increase in stratospheric ozone during November–December and decrease during January–February (Fig. 4d) induced by ozone-circulation feedback is caused by enhanced dynamical transport. We focus on the role of the BDC in driving the ozone increase in early-winter and its decrease in mid-winter, investigating the reasons for the reversal. Figure 6 shows the trend in stratospheric ozone budget from November to February between 10 and 250 hPa in the polar regions (65°–90°N) in the pre-2000 period, which is decomposed into BDC and eddy transport of ozone (calculated by Eqs. (11), (12)). In the ensemble control experiments, from November to December (early winter), the total ozone budget shows a significantly positive trend, indicating an increase in ozone concentrations. This trend is primarily driven by the*“

***sum of BDC and eddy transport. In mid-winter, the trend in ozone budget weakens and changes to negative, indicating a leveling off of increased ozone concentration. In contrast, in the ensemble O3clm experiments, the trend in the ozone budget is opposite to those in the ensemble control experiments and is not statistically significant from November to February. This demonstrates that during early winter, the accelerated BDC intensifies poleward ozone advection through directly transports ozone-rich air masses from tropical reservoirs to polar region, and enhances downward transport of ozone from the upper stratosphere to lower stratosphere. The transport of ozone due to ozone-circulation feedback is reconfirmed by the difference between the ensemble mean of the control and O3clm experiments. In January, the difference between the two experiments shows an intra-seasonal reverse in ozone transport, indicating that the ozone-circulation interactions can also give feedback to ozone concentrations.*"**

For a detailed explanation, please see our replies for your major comment#2.

Line 222: "observed" --- found

Response: Corrected, thank you.

Lines 301-310: Which term in equation (5) causes the reversal of the PV gradient? Also see my major comment 2.

Response: Thank you for your comment. We futher analyze which term dominates the change in $\bar{q}_\varphi$. Figure R3 shows the pattern of the difference in $\bar{q}_\varphi$ between the high ozone period (1980−1985) and the low ozone period (1997−2002). According to the Eq. (4), the first term of $\bar{q}_\varphi$ does not change with the atmospheric state. Therefore, the second term ($-[\frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}]_\varphi$; hereafter referred to as the U_{yy} term

or barotropic term) and the third term ($-\frac{f^2}{\rho_0}(\rho_0 \frac{\bar{u}_z}{N^2})_z$; hereafter referred to as the U_{zz} term or baroclinic term) are investigated. In the ensemble control experiments, note that the pattern of responses in the U_{zz} term is similar with $\bar{q}_\varphi$ (Figs. R3 and R5). This implies that changes in $\bar{q}_\varphi$ over the Arctic in the stratosphere are mainly due to the U_{zz} term. The baroclinic term plays a dominant role in modulating the $\bar{q}_\varphi$ in the Arctic stratosphere. Similar results were obtained in a study from Hu et al. (2022). A reversal of $\bar{q}_\varphi$ in the upper troposphere and lower stratosphere (UTLS) over 60–70°N (Fig. R3a) leads to a reversal of the RI from November to December. In the ensemble O3clm experiments, there is no significant $\bar{q}_\varphi$ increase in the UTLS region in November, nor did the baroclinic term provide favorable conditions (Fig. R5d). This suggests that ozone-climate interaction promotes planetary wave upward by affecting the baroclinic term, which in turn induces an increase in RI.

More detailed information please refer to the reply to the major comment #2.

Lines 447-449: Please explain what dynamical feedback mechanisms you are referring to here.

Response: We appreciate the reviewer's request for clarification. The dynamical feedback mechanisms are the interactions among ozone changes, wave propagation, and the BDC. They collectively influence the Arctic stratospheric dynamics. These mechanisms are summarized as follows: (1) Ozone-induced changes in wave propagation: Nathan and Cordero (2007) pointed that wave-induced ozone heating decrease wave drag in the lower stratosphere by about 25%, favoring planetary wave propagation at this altitude. Additionally, they pointed

out that photochemically accelerated cooling due to ozone augments the Newtonian cooling and increases the wave drag by a factor of two in the upper stratosphere, which is in accordance with our finding that ozone-climate interactions enhance the upper stratospheric EP flux convergence. (2) BDC strengthening and temperature feedback: Enhanced wave activity leads to stronger downwelling in the Arctic region during early winter, which adiabatically warms the lower stratosphere. This dynamical warming, in turn, offsets the direct longwave radiative cooling effects of increased ozone. Meanwhile, the enhanced BDC associated with ozone changes would further increase rich ozone transport from middle latitudes/upper stratosphere to the Arctic lower stratosphere, leading to the positive ozone trends during early winter.

In the revised paper, we replaced "dynamical feedback mechanisms" with "ozone-circulation feedback" which has been mentioned in the preceding analysis, in order to avoid misleading. The revised text as following (see lines 641-650):

"*The ozone-climate interactions are crucial processes in modulating above-mentioned Arctic stratospheric temperature trends. Similar to earlier findings, our study highlights the role of planetary wave activity and BDC in influencing Arctic stratospheric temperature. The present study provides more detailed information on the ozone-circulation feedback processes driven by ozone-climate interactions. The ozone-circulation feedback of interest are primarily the interactions between ozone changes, wave propagation, and BDC, which regulate the dynamics of the Arctic stratosphere. Ozone-induced changes in wave propagation could modulate the vertical motions in the Arctic lower stratosphere, leading to changes in stratospheric temperature and circulation. The ozone transport associated with circulation changes could give feedback effect on polar ozone redistribution.*"

Lines 456-458: You need more ensemble members to assess and reduce experimental uncertainties

Response: Thanks for your comment. We acknowledge that using one ensemble members limits the robustness of our results, particularly in distinguishing the effects of interannual variability from long-term trends. Therefore, in the revised manuscript, we used 5 ensemble experiments (see lines 245-247):

"*Two groups of ensemble climate model experiments (i.e., the control experiment and O3clm experiment) use identical boundary conditions and initial conditions. Each group simulation consists of 5 ensemble members, with initial temperature conditions randomly perturbed.*"

The analysis of new results derived from ensemble experiments can be found in Main comment #2 of the reviwer 1.

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