Response to Community'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 reviewer for your important comments and assistance on our manuscript. The main revisions are summarized as follows:

1. The 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.

2. We provided a detailed response to examine how circulation changes affect Arctic stratospheric ozone's trend. Especially, whether the Brewer-Dobson Circulation (BDC) drive early winter ozone trends.

3.We investigated the role of ozone increase and ozone–circulation interactions in the reversal of the refractive index (RI) from November to December.

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

Response to Comments of Community

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):

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

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;** $\boldsymbol{M}$ **is the eddy flux vector, which is represented as:**

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

$\nabla\cdot \boldsymbol{M}$ **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.

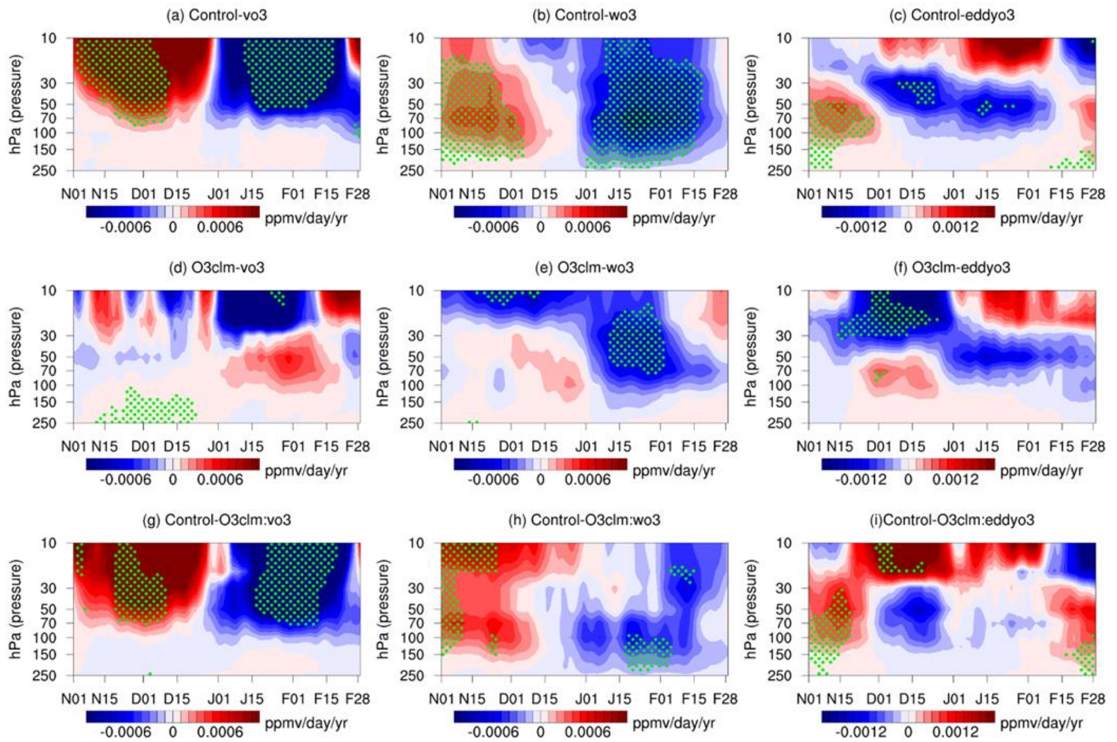

Figure R1. Dynamically produced ozone concentration trend, decomposed into (a, d and g) meridional and (b, e and h) vertical BDC transport and (c, f and i) eddy transport between 10–150 hPa in the polar regions (65°–90°N) from November to February, derived from (a–c) the ensemble control, (d–f) the O3clm 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 $-\frac{f^2}{\rho_0}\left(\rho_0\frac{\overline{u_z}}{N^2}\right)_z = \left(\frac{f^2}{HN^2} + \frac{f^2}{N^4}\frac{\mathrm{d}N^2}{\mathrm{dz}}\right)\overline{u_z} - \frac{f^2}{N^2}\overline{u_{zz}}$ **, 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).

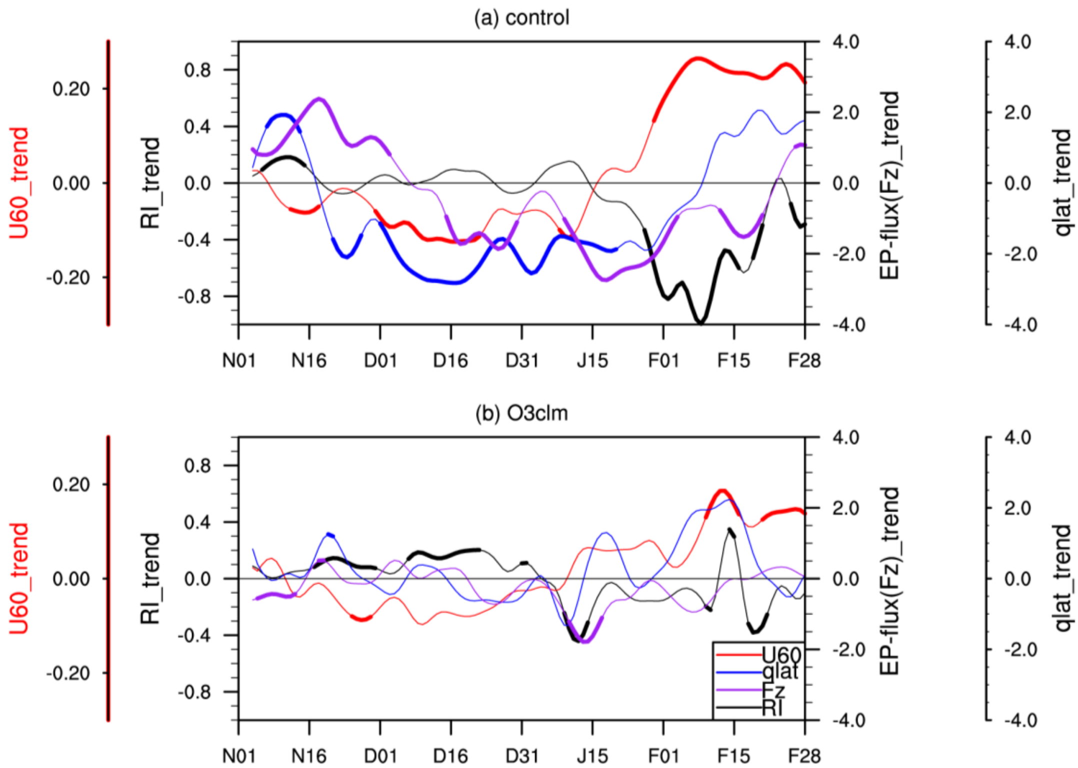

Figure R2. Daily evolution of the trends in the RI (black lines), vertical component of the E-P flux (F_z; purple lines), $\bar{q}_\varphi$ (blue lines), U60 (zonal wind at 60°N; red lines) before 2000 at 50–150 hPa averaged in mid-latitude (45°–75° N) from 1 November to 28 February, derived from (a) 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 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, the pattern of responses in the U_{zz} 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 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 $\bar{q}_{\varphi}$ 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.

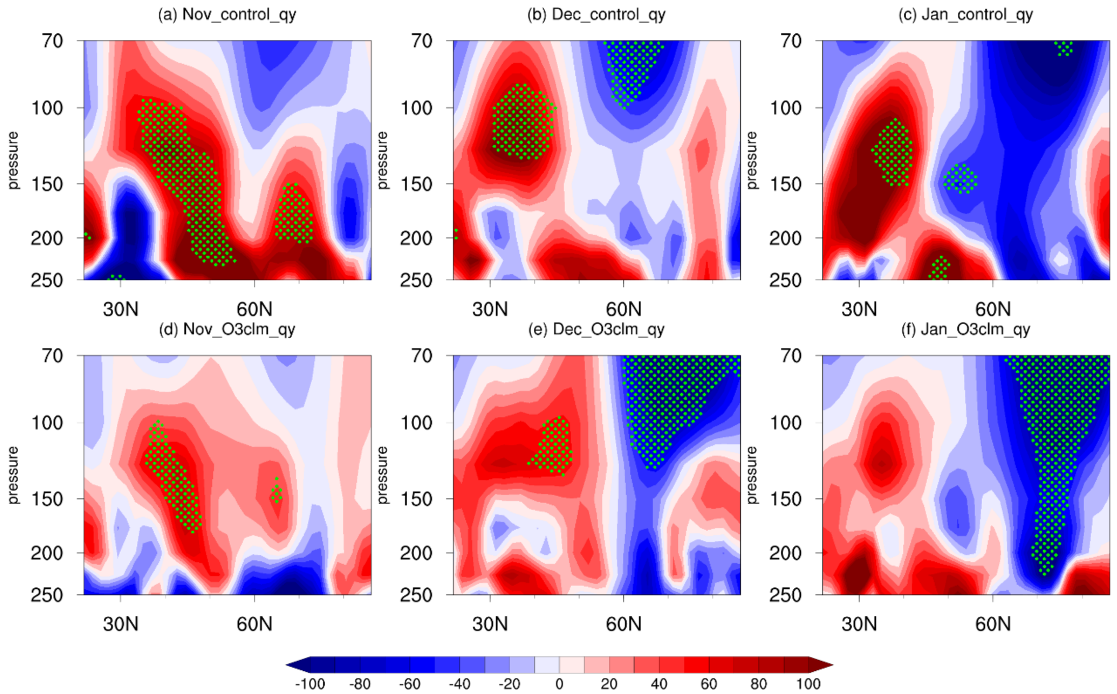

Figure R3. Altitude-latitude cross-section of difference in $a^2 \cdot \bar{q}_{\varphi}$ between the high

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.

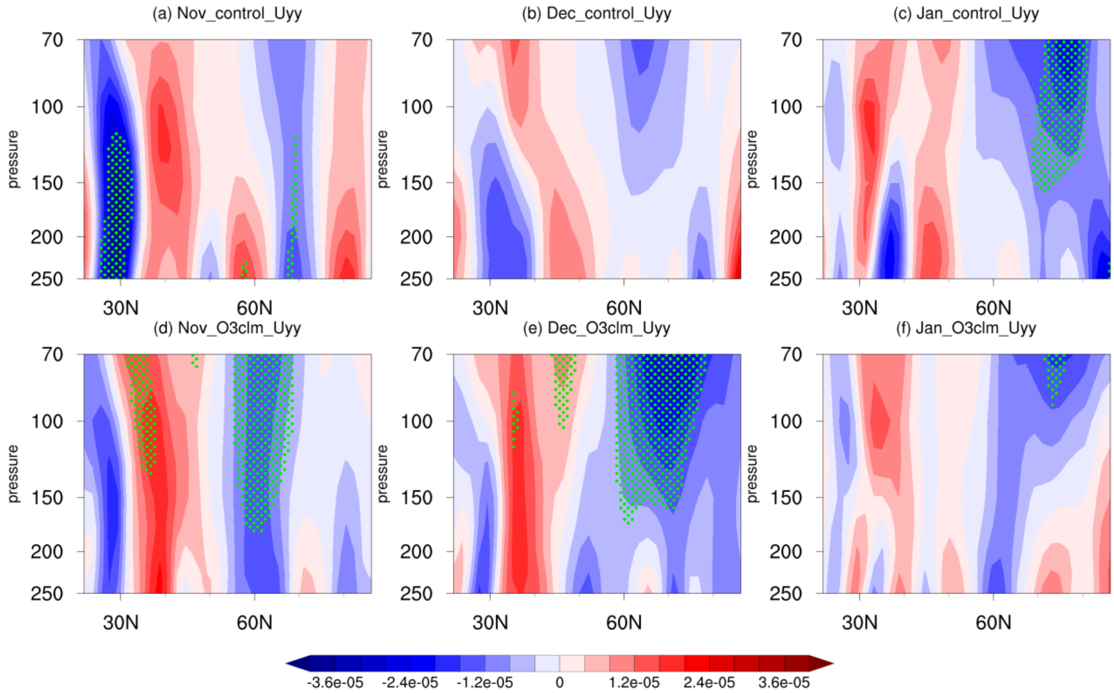

Figure R4. Same as Figure R3, but for the $-[\frac{(\bar{u}\cos\varphi)_\varphi}{a\cos\varphi}]_\varphi$ **(U_{yy} term or barotropic).**

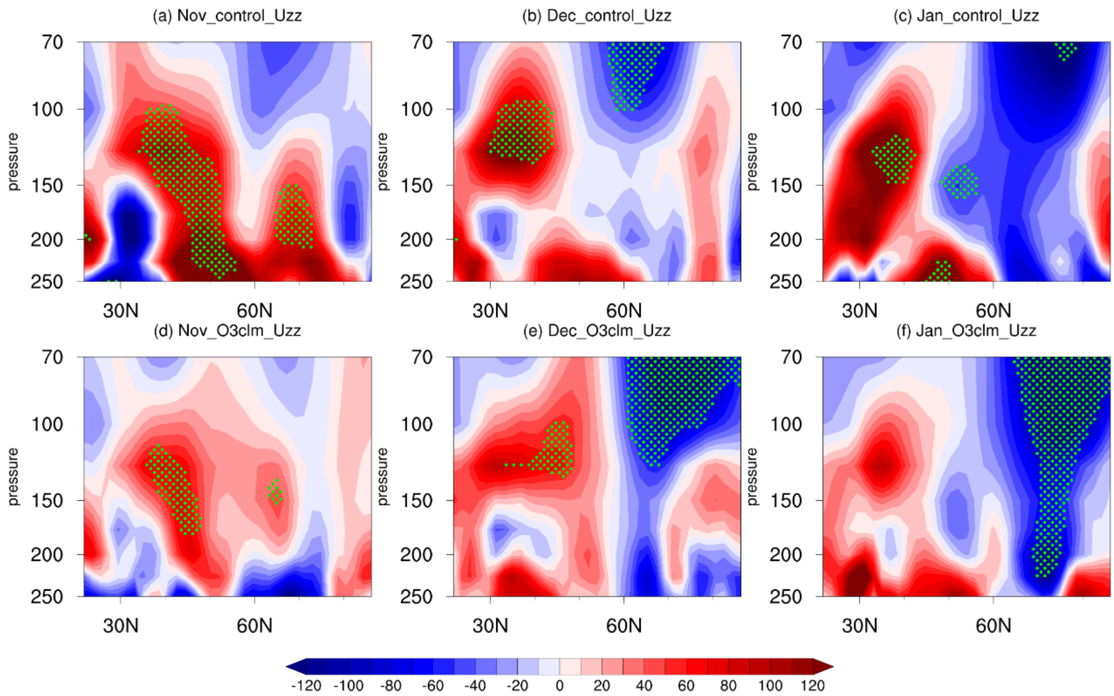

Figure R5. Same as Figure R3, but for the $-a^2 \cdot \frac{f^2}{\rho_0}(\rho_0 \frac{\bar{u}_z}{N^2})_z$ **(U_{zz} term or baroclinic).**

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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