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 reviewer for his/her important comments and suggestions on our manuscript. The main revisions are summarized as follows:

1. **We moved the formulas and equations of wave refractive index and TN wave activity flux into Supplementary Information.**

2. **The radiative heating analysis (the original Fig. 11) has been placed as the first figure in the mechanism explanation (now Fig. 5) to clearly connect ozone-driven temperature changes with dynamical feedbacks.**

3. **We added a new schematic diagram (Figure 11) to illustrate the proposed mechanism, clarifying how ozone-climate interactions drive stratospheric temperature trend changes.**

Response to Comments of Reviewer #1

I appreciate the authors efforts to include more ensemble members and to adapt the ozone climatology according to my previous suggestions. I think these changes have considerably improved the results of the paper. However, I think this paper needs some restructuring and rewriting in some places before it can be presented to the audience of this journal. Specifically, I suggest:

- Removing the equations on pages 4-6. The long equations hamper the flow of the paper. The interested reader can refer to the mentioned references.

Response: We appreciate the reviewers' positive feedback. Following this suggestion, the equations of refractive index and Takaya-Nakamura (T-N) wave-activity flux (the original Eqs. (4) and (10)) are moved to the Supplementary Information to ensure the readability of the paper, while retaining other key equations in the main text to support mechanistic explanations.

- More clearly highlighting the main pathway by which ozone trends affect temperature and circulation. In the paper, the authors make it sound as if ozone had a direct impact on the circulation and the order of the Figures is confusing. However, the actual pathway by which ozone affects the circulation is via changes of the stratospheric temperature. Therefore, I suggest moving Fig. 11 (short- and longwave heating) forward (after Fig. 4), and build the mechanistic explanation from there.

Response: Thanks for your nice suggestion. We have moved the original Figure 11 (Trends of shortwave and longwave heating rates) after Figure 4. The revised article has more clearly logic: Figures 3-4 (Temperature Trend) →Figure 5 (Radiative Feedback) →Figures 6-8 (Dynamic Feedback).

- I think a schematic outlining the proposed mechanism would help the reader to better follow the arguments made. My understanding is that in early winter, an increase of the BDC between 1980-2000 led to more ozone being transported to the pole, which decreased stratospheric temperatures during Nov-Dec due to an increase in longwave emission. This then probably leads to an increase in the BDC (mechanistic link from temperature decrease to an increase in BDC is not entirely clear to me from the manuscript), because the positive temperature difference between the control and clim_O3 run can only be due to adiabatic heating due to circulation changes (which outweighs the longwave cooling), as shown in Fig. 5.

Response: Thank you for your suggestion. We have added a new conceptual diagram (Fig. 11 in the revised manuscript in Lines 587-592) that depicts the ozone–climate interaction processes as follows: "*An integrated picture depicting the mechanisms before 2000 is shown in Figure 11.*"

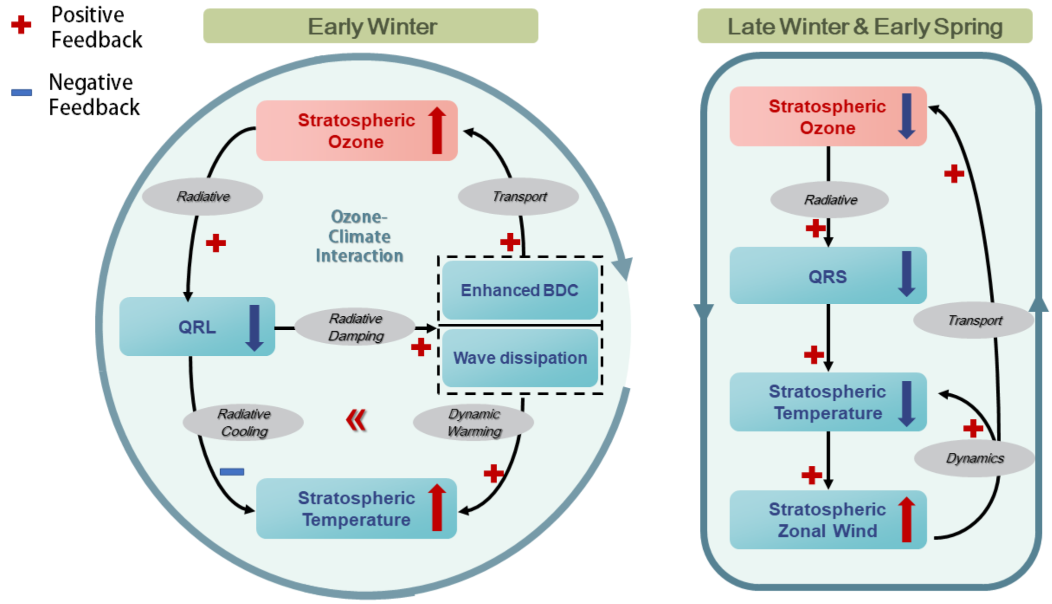

Figure R1 Schematic diagram of the ozone feedback mechanisms: the effects of early-winter ozone increase and late-winter/early-spring ozone decrease in the polar regions of the Northern Hemisphere on stratospheric temperature trends through ozone-climate interactions. Shown are impacts of ozone changes on radiation and dynamic, further on temperature in the lower stratosphere.

Its description can be seen from L402 to L413 in section Conclusion and discussion as follows:

"*Notably, the ozone-circulation feedback of ozone-climate interactions plays a key*

role in modulating this trend. Specifically, in early winter, ozone-circulation feedback can create an atmospheric state favorable for upward wave propagation, which is induced by the increases of $\bar{q}_{\varphi}$ in mid-latitude, and E-P flux convergence (Figs. 8, S1), which could lead to a strengthened BDC (Fig. 6) and thereby a positive trend in temperature and ozone (Figs. 3 and 7) during early winter. These trends in the BDC and planetary wave activity are predominantly driven by planetary wavenumber 1 (Figs. 6, 8). The wave-induced ozone heating increases lower-stratospheric wave propagation (Figs. 8, S1), and subsequently weakens the polar vortex during mid-winter (Fig. S1). Then, the upward propagation of planetary waves is suppressed, and consequently, the Arctic stratospheric temperature show opposite trends in January and February to early winter. During early spring, when solar radiation reaches the polar regions, reduction in ozone shortwave heating during the ozone-depletion period results in the negative temperature trend during spring (Fig. 5). After 2000, the stratospheric temperature response to ozone changes is weaker than that before 2000 (Figs. 9, 10)."

- Are Figures 8, 9 and 10 needed for the mechanistic explanation? Otherwise move it to the supplement for better readability. I would also consider expanding Fig. 8 to include March and April.

Response: Thank you for this helpful suggestion. The initial Fig. 8 has been relocated to Supplementary Information (Fig. S1). As the reviewers noted, Figures 9-10 are not very helpful for mechanism interpretation, so we have deleted the two figures in the revised manuscript to improve readability. The original temporal scope (Fig. S1) was retained because dynamic feedbacks dominate ozone-climate interactions in winter, while radiative feedback is the main driver in early spring.

In addition:

- In Fig. 2 it looks like in b) and c) you show twice ERA5 instead of CESM? Could this be a data error?

Response: We ensured that ERA5 (orange) and CESM (brown) were labeled

correctly. ERA5 is used to verify the reliability of the phenomenon of stratospheric temperature trends.

- Does your 1980-clim experiment use fixed SSTs? If so, which years were used to produce the SST climatology? Using only SSTs from a specific year (e.g. 1980) might skew the ozone climatology.

Response: Yes, the 1980-clim experiment used fixed SSTs in the year of 1980 according to the following reasons:

1. The year 1980 represents a period of relative stability before the rapid increase in ozone-depleting substances (ODS). At that time, stratospheric ozone had not yet experienced significant anthropogenic emitted ODS depletion (WMO, 2018).

2. Using fixed SSTs (prescribed as the 1980 climatology) helps isolate stratospheric dynamical responses by preventing interference from interannual variability, decadal variability or multi-decadal variability in sea surface temperatures.

Reference:

WMO: Scientific Assessment of Ozone Depletion: 2018, World Meteorological Organization Rep. 58, Geneva, Switzerland, 2018.