Responses to Referee's Comments

Weakening of Antarctic Stratospheric Planetary in Early Austral Spring Since the Early 2000s: A Response to Sea Surface Temperature Trends

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Responses to Referee 2

The authors present a comprehensive study on the trend in the planetary wave activities in September over the Antarctic stratosphere from 1980 to 2018. Using reanalysis data and numerical simulations, the authors intend to answer two questions: (1) Has the stratospheric planetary wave activity trend in the southern hemisphere been shifting since 2000? (2) What are the factors responsible for the trend shifting. The authors did a good job in address the first question. For the second question, there is a large room for improvement.

Response:

We appreciate the reviewer for sparing time to go through the manuscript, providing useful comments and valuable suggestions to improve our manuscript. We have revised the manuscript carefully according to the reviewer's comments and suggestions. The detailed responses are listed as follows:

General comments:

The authors stated that the changes in the stratospheric planetary wave activity trend in the southern hemisphere may be related to change in SST, stratospheric ozone, and IPO. This paper discussed the effect of SST mostly, which was well done. However, I agree with the other reviewer that time-lags should be further considered in the analysis. The effect of stratospheric ozone is poorly addressed. In the abstract and text, it is stated "The responses of stratospheric wave activities in the southern hemisphere to stratospheric ozone recovery is not significant in simulations". This provides no useful information to the reader as it did not answer if there is such an effect. How well does the CESM model simulate the evolution of stratospheric ozone? Specifically, Figs.2a and 2b show a clear shift of the trend in stratospheric planetary wave activity over the southern hemisphere around 2000. It would be useful to compare it with the time series of both SST and stratospheric ozone, and both are missing in this paper. Previous studies have shown an inflection point around 1998 in the time series of *stratospheric ozone from 1980-2018. An inflection point may not be very apparent in the SST time series. These may provide the authors with some hints for further analysis.*

Response:

Thanks for the comments. The comments include three parts and we will give our responses separately.

1. Responses to comments about time lags

The reviewer's first concern is about time lags of the responses, which is the same as the second comment raised by the other reviewer. As the detailed description about numerical experiments has been given in response to the comment #2 from the other reviewer, we just list some main points and display the supporting figures here.

Firstly, we performed an additional experiment ssttropAug in September SST anomalies are excluded to clarify whether the weakening of Antarctic stratospheric wave activity is induced by the tropical SST trend at the same month. The responses of tropospheric wave sources and stratospheric wave activities in ssttropAug are shown in Figs. R1a-c and Figs. R1d-f, respectively. Note that the anomalies of subpolar tropospheric geopotential height in September forced by change in tropical SST in August does not superpose on their climatological patterns in an obvious out-of-phase style (Figs. R1a-c). The anomaly of wave-1 component of geopotential height shows slight in-phase overlap with its climatology over subpolar region (Fig. R1b). Accordingly, the responses of stratospheric wave activities over subpolar of southern hemisphere are not significant (Figs. R1d-f). The decrease of September vertical wave flux induced by SST changes in August is negligible comparing to the experiment includes anomalous SST forcing in September (Figs. R1g), which suggests that the tropical SST trend in September plays a dominate role in weakening of stratospheric wave activity at the same month.

Secondly, we use a linear barotropic model (LBM) (e.g., Shaman & Tziperman, 2007; Shaman & Tziperman, 2011) to quantify the time scale for propagation of tropical anomalies to high latitudes. The LBM simulated streamfunction anomalies are shown in Figs. R2b-i. Note that the anomalies in tropics only take a few days to arrive the high latitudes in Southern Hemisphere. After about four days, a stable anti-phase superposition of streamfunction is well established in extratropical southern hemisphere (Figs. R2f-i). These results are supported by previous studies (e.g., Shaman & Tziperman, 2011), which also indicate that the horizontal propagation of an anomaly in atmosphere takes a few days.

Previous studies also reported that it takes about 4 days for wave-1 to propagate from troposphere into stratosphere and 1-2 days for wave-2 (e.g. Randel, 1987). We agree with the reviewer that the tropical oceans affect the stratosphere at mid-high latitudes with a lag of several days. However, the SST forcing field applied in CESM is on monthly scale. It is reasonable to use September SST trend to drive and explain the trends of extratropical circulation and wave activity at the same month.

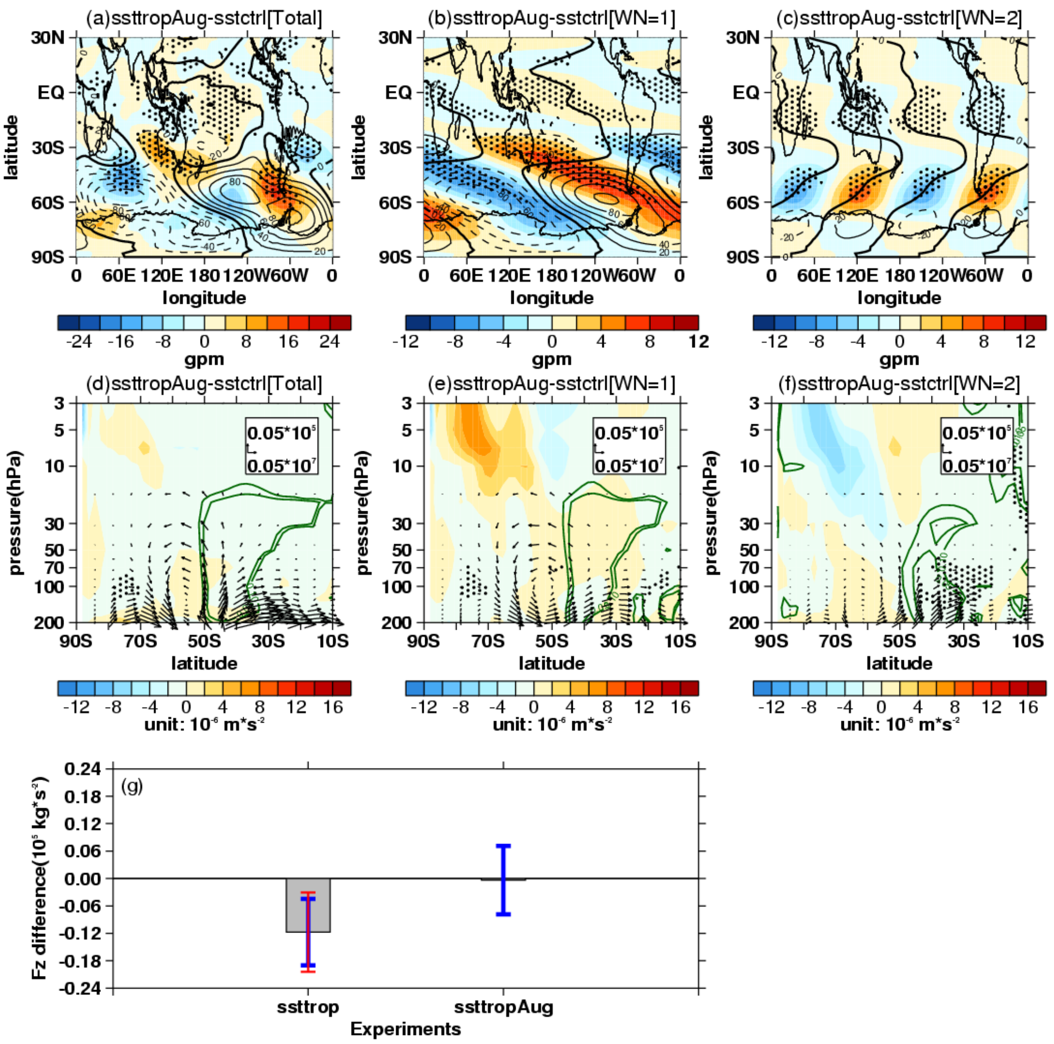

FIG. R1. (a-c) The responses of tropospheric wave sources in experiment ssttropAug:

differences of (a) 500 hPa geopotential height zonal deviations with their (b) wave-1 component and (c) wave-2 component between ssttropAug and sstctrl. The mean distributions (contours with an interval of 20 gpm, positive and negative values are depicted by solid and dashed lines, respectively, zeros are depicted by thick solid lines) of them are derived from sstctrl. (d-f) The responses of stratospheric wave activities in experiment ssttropAug: differences of (d) stratospheric E-P flux (arrows, units in horizontal and vertical components are 0.05×10^7 and 0.05×10^5 $kg\cdot s^{-2}$, respectively) and its divergence (shadings) with their (e) wave-1 component and (f) wave-2 component between ssttropAug and sstctrl. The stippled regions in Figs. R1a-f represent the mean difference significant at/above the 90% confidence level. The green contours from outside to inside (corresponding to p=0.1 and 0.05) in Figs. R1d-f represent the mean differences of vertical E-P flux significant at the 90% and 95% confidence levels, respectively. (g) Mean differences (grey pillars) and corresponding uncertainties (error bars) of Fz (area-weighted from 200 hPa to 10 hPa over 70°S-50°S) between sensitive experiments and the control experiment. The blue and red error bars reflect the 90% and 95% confidence levels calculated by two-tailed t test, respectively.

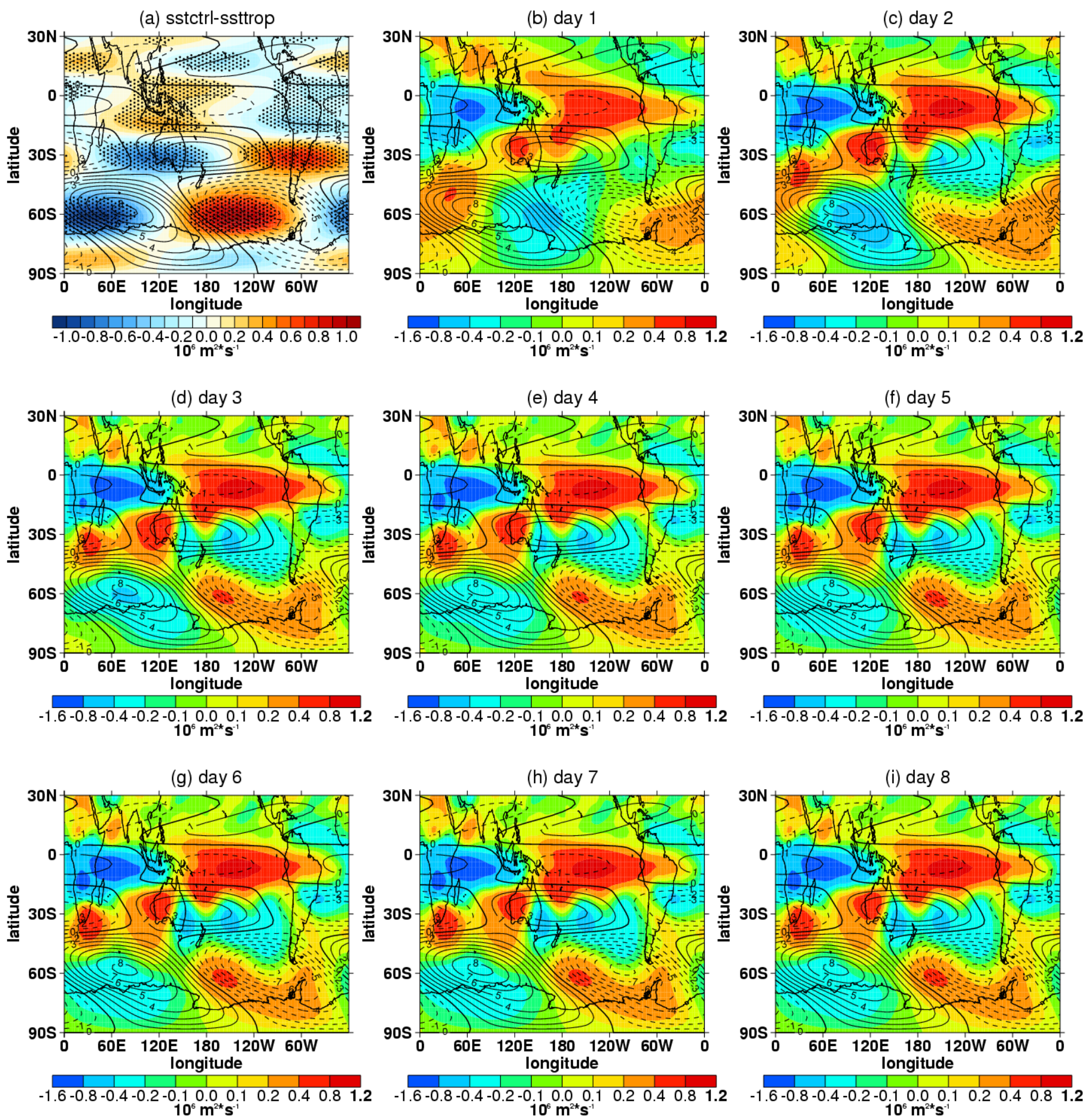

FIG. R2. The background field (contours with interval of 10^6 $m^2 \cdot s^{-1}$, positive and negative values are depicted by solid and dashed lines, respectively, zeros are depicted by thick solid lines) of streamfunction derived from sstctrl and the responses (shading) of streamfunction derived from (a) ssttrop and (b-i) the first to eighth model days in LBM.

2. Responses to comments about ozone time series and effects of stratospheric ozone

The reviewer suggests that it is necessary to add ozone time series in the manuscript and give more specific discussions about impacts of ozone recovery on stratospheric wave activity. Following the suggestions, we have added a new section after Section 3 and some text in abstract to discuss the responses of stratospheric wave activities in southern hemisphere to ozone recovery. The main contents we modified are shown as follows:

a) The newly added Section 4:

Response of Antarctic stratospheric wave activity to ozone recovery

Previous studies have suggested that ozone depletion and recovery are important to climate shift that occurred around 2000 in the southern hemisphere during austral summer (e.g., Son et al., 2008; Thompson et al., 2011; Barnes et al., 2013; Banerjee et al., 2020). The impacts of stratospheric ozone changes on Antarctic wave propagation during austral summer have also been studied previously (e.g., Hu et al., 2015). However, whether ozone recovery in September explains the weakening of stratospheric planetary waves at the same month remains uncertain. The correlation between detrended time series of September Antarctic total column ozone (TCO) derived from SBUV and stratospheric vertical wave flux (Fz) is 0.70 (p=0.0011) during 2000-2017. The increase of wave activity in polar stratosphere will warm polar stratosphere and suppresses the formation of PSCs, and hence, slow down the ozone depletion (e.g., Shen et al. 2020a). Therefore, the Antarctic ozone and stratospheric wave activity show statistically significant positive correlation. Theoretically, heating effects caused by ozone recovery in Antarctic stratosphere may also decelerate the Antarctic stratospheric polar vortex and induce more waves to propagate into stratosphere (Andrews et al., 1987; Holton et al., 2004). These preliminary analysis cannot verify that the ozone recovery is responsible for weakening of stratospheric wave activity. The role of ozone recovery in stratospheric wave changes needs to be further explored by model simulations. In this section, we use a group of time-slice experiments (O3ctrl and O3sen) to address this issue.

Figures R3 show the time series and piecewise trends of September TCO in the Antarctic during 1980-2017. As reported by previous studies (e.g. Angell and Free, 2009; Banerjee et al., 2020; Krzyścin, 2012; Solomon et al., 2016; WMO, 2011; Zhang et al., 2014), the Antarctic ozone show a significant decline during 1980-2000 (Figs. R3a, b, c) and a slight recovery during 2001-2017 (Figs. R3a, d, e). The recovery trend is calculated with data in 2002 removed because the large poleward transport induced by SSW in 2002 leads to extreme values of ozone (e.g., Solomon et al., 2016). In addition, the correlation of TCO between MERRA-2 and SBUV datasets is 0.61 ($p=4.5\times10^{-5}$), suggesting the changes of TCO derived from the reanalysis dataset and the observations have a good consistency. Thus, in order to get three-dimensional structure of ozone changes, the ozone data from MERRA-2 are used to make forcing fields for CESM. As described in Section 2, a control experiment (O3ctrl) forced by climatological ozone and a sensitive experiment forced by the linear increment of global ozone in September during 2001-2017 are conducted to explore the impacts of ozone recovery. The pattern of ozone forcing fields is similar to its trend patterns (Figs. R3d, e; Figs. R4a, b). Other details of these two experiments have been given in Section 2 and Table 2.

Fig. R5 and Fig. R6 show the responses of wave activity and wave propagation environment in experiment O3sen. Note that the significant ozone recovery over south pole mainly appears in lower stratosphere (about 200 hPa to 50 hPa) (Fig. R3e). In most southern polar regions from 50 hPa to 3 hPa, the ozone recovery is not significant. The features are attributed to limitation of ODSs emission and reduction of heterogeneous reaction on PSCs, which mainly distribute in lower stratosphere. Ozone recovery in polar lower stratosphere absorbs more ultraviolet radiation and causes cooling in Antarctic troposphere (Fig. R5a). To maintain thermal balance, zonal wind accelerates below 200 hPa over 60°S-70°S (Fig. R5b).

The changes of zonal wind and temperature forced by ozone recovery induces the change of wave propagation environment. The refractive index (RI) is a good matric to reflect the atmosphere state for wave propagation. Theoretically, planetary wave may tends to propagate into large RI regions (Andrews et al., 1987). The responses of RI and its terms are shown in Figs. R5c-f. Note that the second term of RI does not change with atmospheric state and the third term of RI is insignificant compared to the first term (Hu et al., 2019). Previous studies indicate that changes in zonal mean potential vorticity meridional gradient $\bar{q}_{\varphi}$ could explain the changes in RI in middle and high latitudes (e.g., Hu et al., 2019; Simpson et al., 2009). Consistent with these studies, the pattern of $\overline{q}_{\varphi}$ show some similarity with pattern of RI (Figs. R5c, d), especially in lower stratosphere over subpolar regions (Figs. R5c, d). According to the Eq. (5), the first term of $\overline{q}_{\varphi}$ does not change with atmospheric state. Therefore, the second term ($-[\frac{(\overline{u}\cos\varphi)_{\varphi}}{\cos\varphi}]_{\varphi}$, hereafter uyy term or barotropic term) and the third term ($-\frac{f^2}{\rho_0}(\rho_0\frac{\overline{u}_z}{N^2})_z$, hereafter uzz term or baroclinic term) are investigated. Note that the pattern of responses in baroclinic term is similar with $\overline{q}_{\varphi}$ (Figs. R5d, f). The uzz term also can be written as $(\frac{f^2}{HN^2}+\frac{f^2}{N^4}\frac{dN^2}{dz})\overline{u}_z-\frac{f^2}{N^2}\overline{u}_{zz}$. Meanwhile, zonal wind acceleration in upper troposphere weakens the vertical shear of u ($\overline{u}_z$) around 200 hPa over subpolar regions, inducing the decrease of baroclinic term and RI in upper troposphere and lower stratosphere (UTLS) over 60°S-70°S (Figs. R5d, f). The responses of RI induce the slight decrease of vertical wave flux in UTLS over subpolar regions (Fig. R6). However, the changes of wave activity in UTLS are not significant in ensemble mean of simulations (Figs. R6a, b, c). Meanwhile, note that the responses of zonal wind and temperature to ozone recovery is not significant above 50 hPa over subpolar regions (Figs. R5a, b), inducing negligible responses of wave propagation environment (Fig. R5c) and wave activity (Fig. R6) in middle and upper stratosphere.

In a word, the significant ozone recovery in Antarctic lower stratosphere changes wave propagation in upper troposphere and lower stratosphere to some extent. However, these weak responses still cannot explain the significant decrease of stratospheric wave flux in September.

b) The abstract:

"Using multiple reanalysis datasets and model simulations, the trends of Antarctic stratospheric planetary wave activities in early austral spring since the early 2000s are investigated in this study. We find that the stratospheric planetary wave activities in September have weakened significantly since 2000, which is mainly related to the weakening of the tropospheric wave sources in the extratropical southern hemisphere. As the Antarctic ozone also shows clear shift around 2000, the impact of ozone recovery on Antarctic planetary wave activity is also examined through numerical simulations. Significant ozone recovery in lower stratosphere changes the atmospheric state for wave propagation to some extent, inducing a slight decrease of vertical wave flux in upper troposphere and lower stratosphere (UTLS). However, the changes of wave propagation environment in middle and upper stratosphere over subpolar region are not significant. The ozone recovery has minor contribution to the significant weakening of stratospheric planetary wave activity in September. Further analysis indicates that the trend of September sea surface temperature (SST) over 20°N-70°S is well linked to the weakening of stratospheric planetary wave activities. The model simulations reveal that the SST trend in the extratropical southern hemisphere (20°S-70°S) and the tropics (20°N-20°S) induce a weakening of wave-1 component of tropospheric geopotential height in the extratropical southern hemisphere, which subsequently leads to a decrease in stratospheric wave flux. In addition, both reanalysis data and numerical simulations indicate that the Brewer-Dobson circulation (BDC) related to wave activities in the stratosphere has also been weakening in early austral spring since 2000 due to the trend of September SST in the tropics and extratropical southern hemisphere."

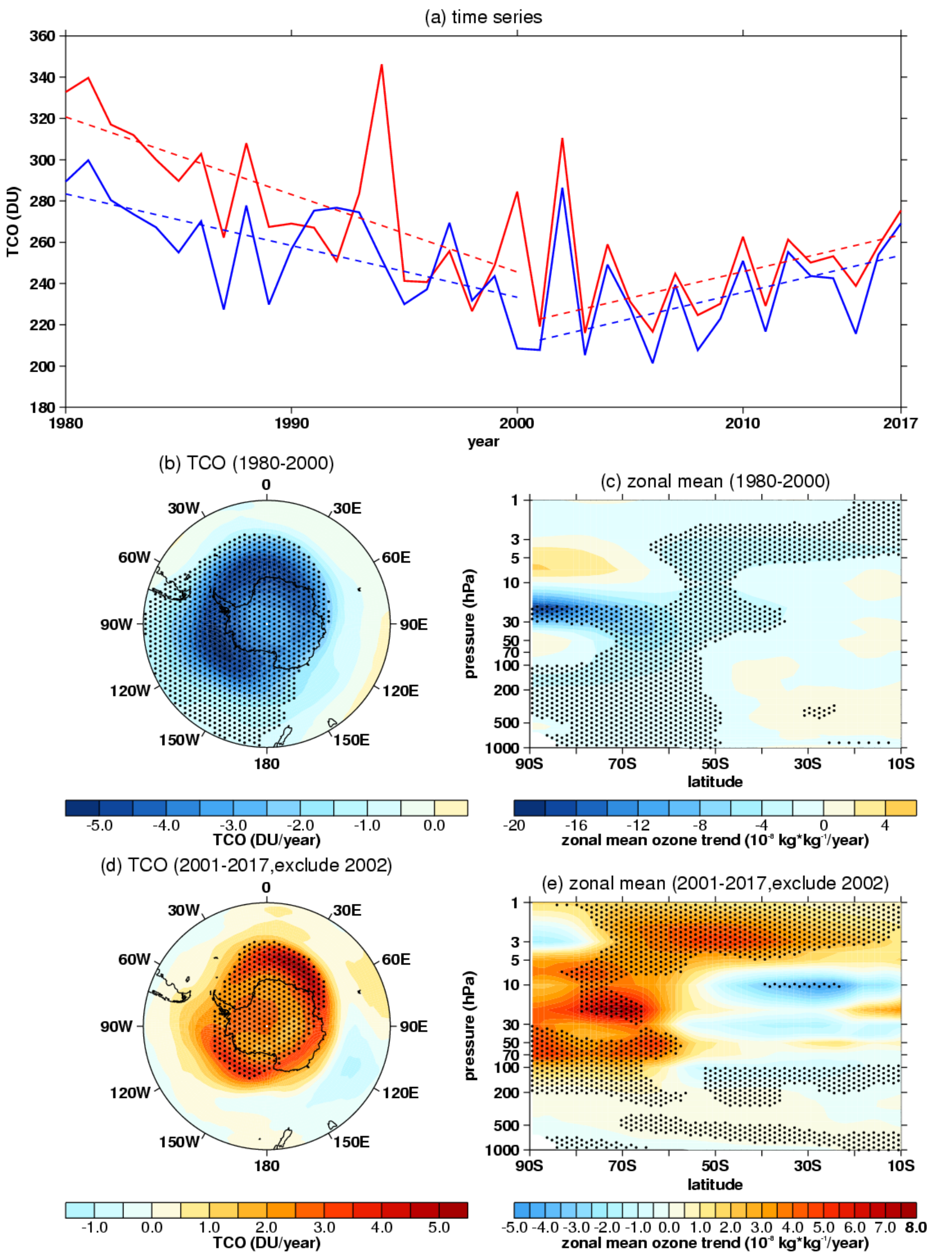

FIG. R3. (a) Time series (solid lines) of aera-weighted total column ozone (TCO) over 60°S to 90°S derived MERRA-2 (red) and SBUV (blue) dataset. The dashed lines represent linear regression of TCO. (b, d) The TCO trends in September during 1980-2000 (b) and 2001-2017 (d) derived from MERRA-2 dataset. The outermost latitude in Fig. R3c, d is 40°S. (c, e) The zonal mean ozone trend on latitude-pressure profile in September during 1980-2000 (c) and 2001-2017 (e) derived from MERRA-2 dataset. The stippled regions in Figs. R3b-e represent trends significant at/above the 90% confidence level. Data in 2002 are removed when trends, regressions and significances are calculated in Fig. R3.

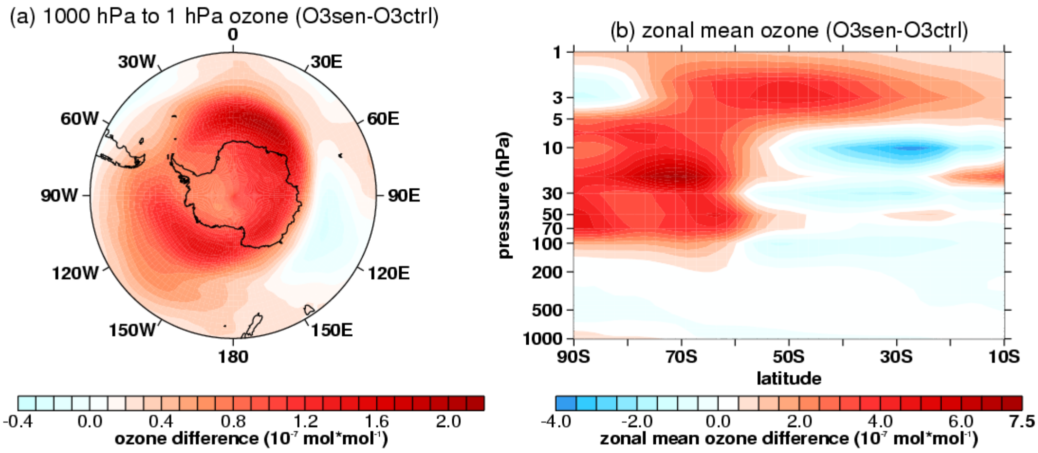

FIG. R4. Difference of horizontal ozone forcing field averaged from 1000 hPa to 1 hPa between O3sen and O3ctrl. The outermost latitude in Fig. R4a is 40°S. Zonal mean difference of ozone forcing fields (b) on latitude-pressure profile in the southern hemisphere between O3sen and O3ctrl.

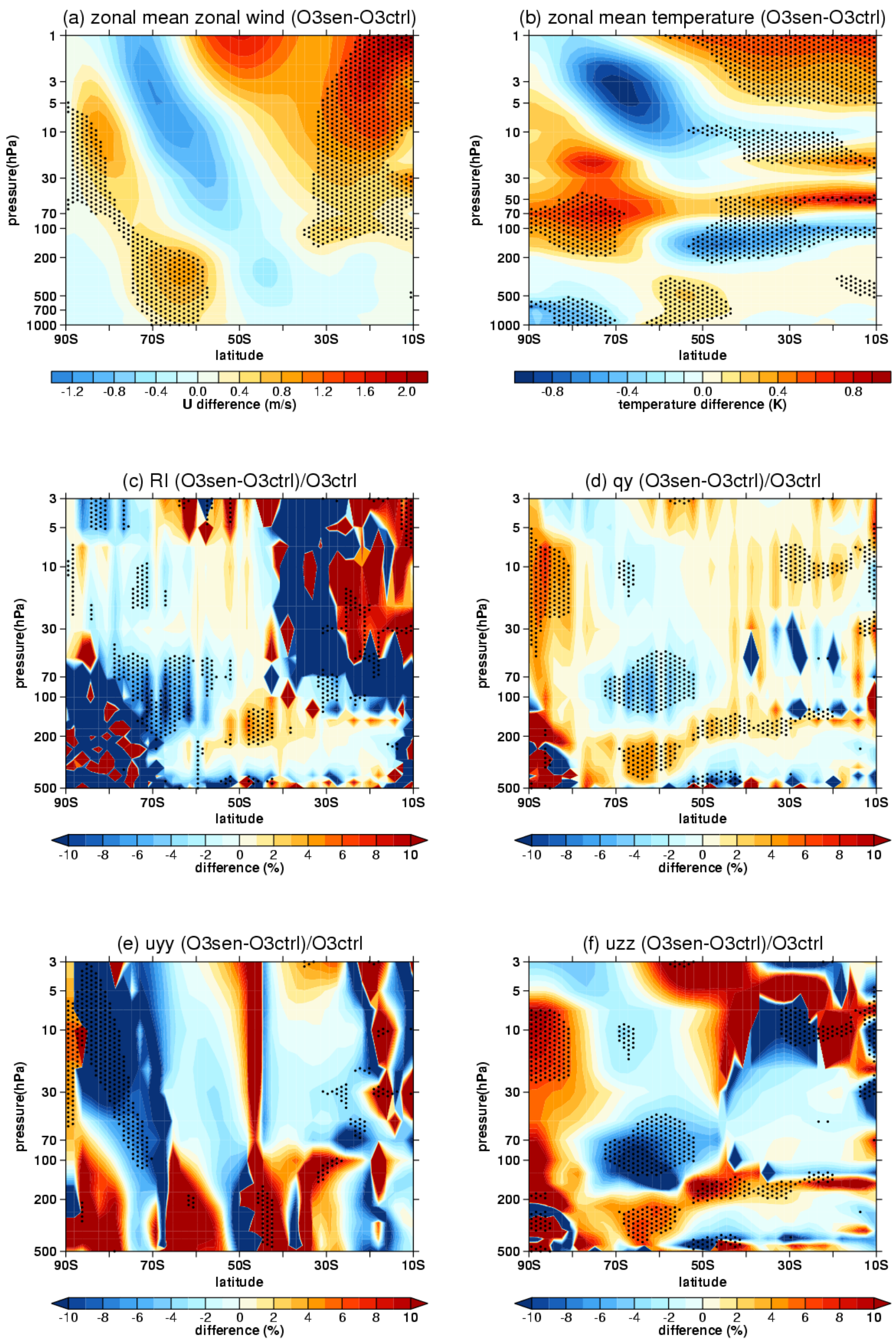

FIG. R5. Difference of (a) zonally averaged zonal wind, (b) zonally averaged temperature, (c) refractive index, (d) $a^2\bar{q}_\varphi$, (e) $-[\frac{(\bar{u}\cos\varphi)_\varphi}{\cos\varphi}]_\varphi$ (hereafter uyy term), (f) $-\frac{a^2 f^2}{\rho_0}(\rho_0 \frac{\bar{u}_z}{N^2})_z$ (hereafter uzz term) between O3sen and O3ctrl. The stippled regions represent the difference significant at/above 90% confidence level.

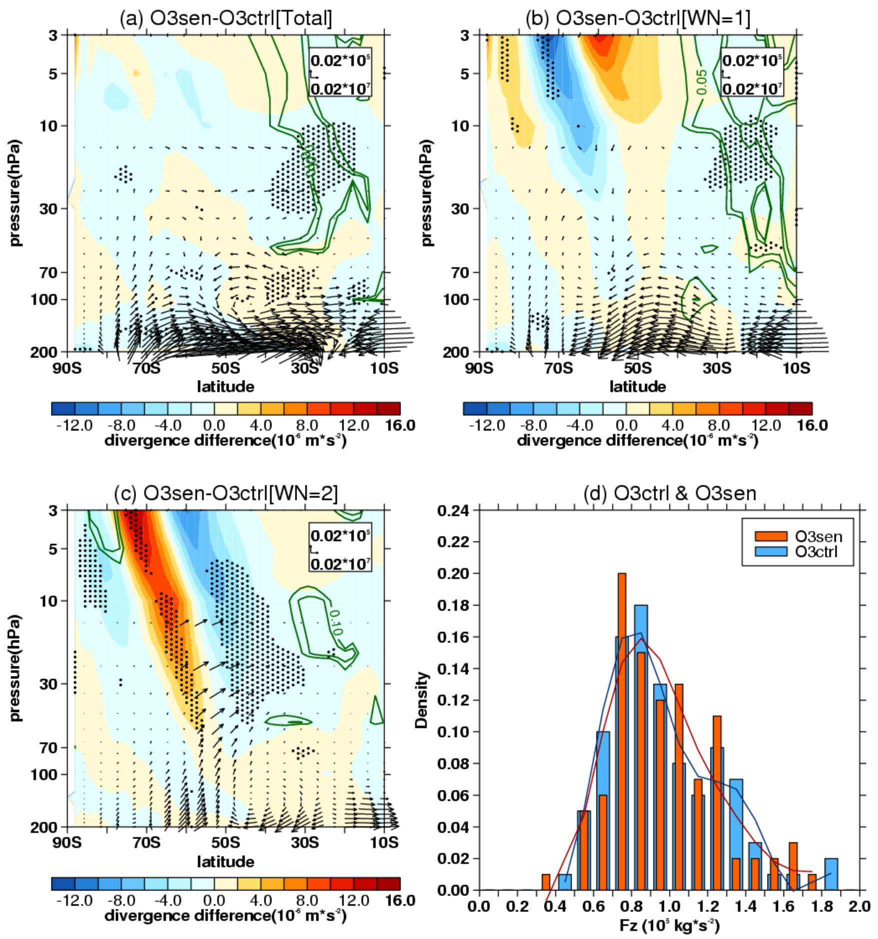

FIG. R6. Differences of (a) stratospheric E-P flux (arrows, units in horizontal and vertical components are 0.02×10^{7} and 0.05×10^{5} kg·s^{-2}, respectively) and its divergence (shadings) with their (b) wave-1 component and (c) wave-2 component between the sensitive experiment (O3sen) and the control experiment (O3ctrl). The stippled regions represent the mean differences of E-P flux divergence significant at/above the 90% confidence level. The green contours from outside to inside (corresponding to p=0.1, 0.05) represent the mean differences of vertical E-P flux significant at the 90% and 95% confidence levels, respectively. (d) Frequency distributions (pillars, blue for O3ctrl and orange for O3sen) of vertical E-P flux (Fz, area-weighted from 200 hPa to 10 hPa over 70°S-50°S) and it 5-point low-pass filtered fitting curves (solid lines, blue for O3ctrl and red for O3sen) derived from 100 ensemble members.

3. Responses to comments about inflection of SST time series

The reviewer suggests that it is necessary to add SST time series in the manuscript and find the inflection of SST to compare it with shift of stratospheric wave activity. We find that the inflections of SST time series around 2000 exist in some regions, which is shown in Fig. R7.

Following the suggestions, we have replaced the Fig. 10 (Fig. 4 in the original manuscript) with Fig. R7 and revised the first paragraph of Section 5 in the revised manuscript. The modified contents are shown as follows:

In addition, there are inflections of SST time series over some regions around 2000. In the southern Indian ocean, SST show insignificant trend during 1980-2000 and significant warming trend during 2000-2017 (Fig. R7c). The subtropical Pacific ocean east of Australia is linked with the Pacific-Southern America (PSA) wave train (e.g. Shen et al., 2020b), and the SST there shows significant warming trend during 1980-2000 and insignificant trend during 2000-2017. The SST in southeast Pacific show insignificant trend during 1980-2000 and significant cooling during 2000-2017 (Fig. R7e). Trends of SST in southern Atlantic ocean are opposite during these two piecewise periods, showing significant cooling trend during 1980-2000 and significant warming trend during 2000-2017. In a word, the spatial pattern of SST trend during 2000-2017 is obviously different from that during 1980-2000 (Figs. R7a, b), which may affect the tropospheric wave sources.

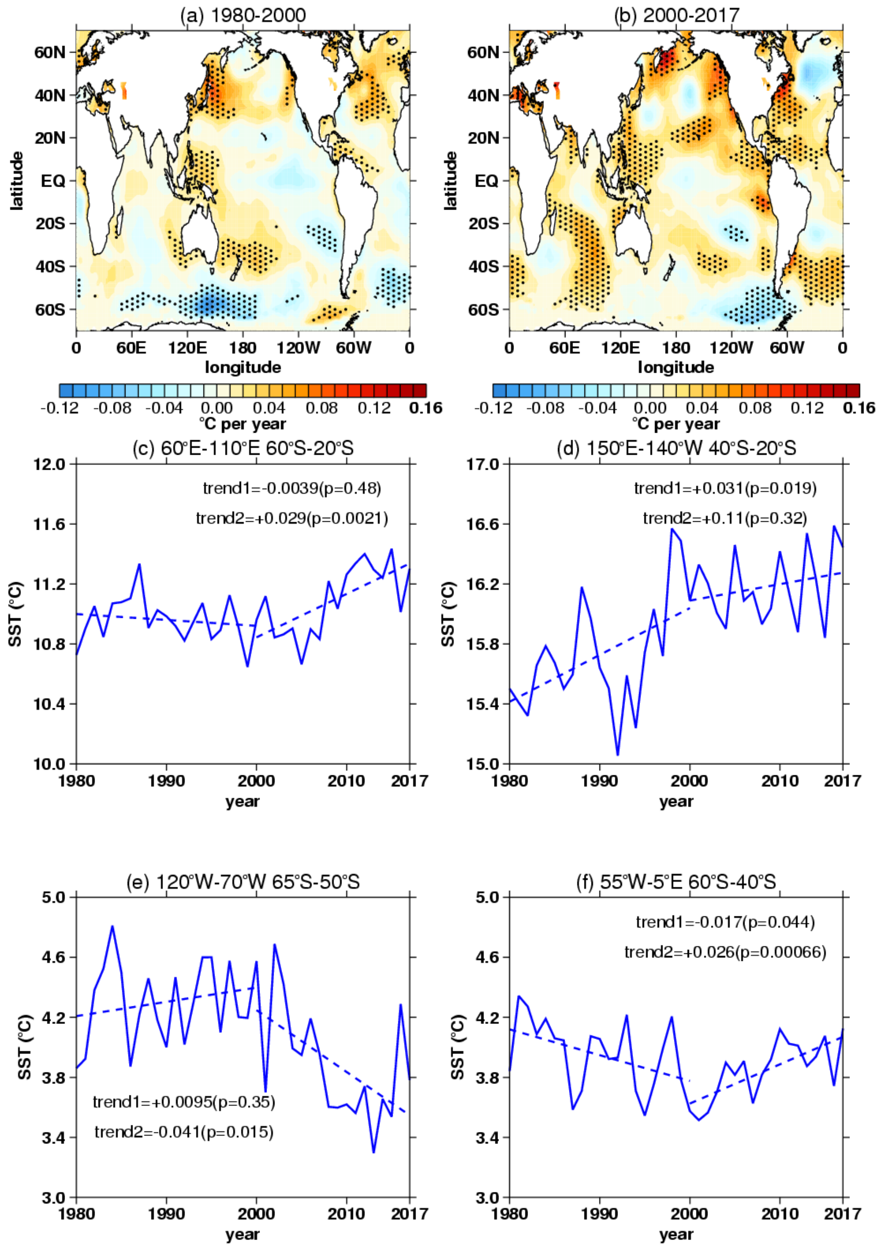

FIG. R7. Trends of SST in September over (a) 1980-2000 and (b) 2000-2017 derived from ERSST v5 dataset. The stippled regions represent trends significant at/above the 90% confidence level. (c-f) Time series (blue solid lines) of SST during 1980-2017 over different regions (titles). The dashed lines represent linear regressions of SST time series on piecewise periods (1980-2000 and 2000-2017). The "trend1" and "trend2" labeled in Figs. c-f represent the trend coefficients and the corresponding significances (bracketed) over 1980-2000 and 2000-2017, respectively.

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Specific:

L94, "…SST trend". Change to "…changes in SST".

Response: Thanks for the suggestion. It has been revised.

L118, "BDC" is defined in the abstract. Should it be defined in the text?

Response: Thanks for the suggestion. BDC is defined as Brewer-Dobson circulation in the text

L148, what is H?

Response: Thanks for the careful check. H is scale height. It is defined after Eq. (4).

L161, add an "a" before the first "zonal", and a "the" before the second "zonal".

Response: Thanks for the careful check. It has been revised

L180-188, provide some references.

Response: Thanks for the suggestion. The reference has been added before Eq. (7) and Eq. (8). The added reference is

Shirley, D., Stanley, W., & Daniel, C.: Statistics for Research (Third Edition), (p. 627), Hoboken, New Jersey: John Wiley & Sons Inc., 2004.

L372, "…the SST trends". Change to "…the change in SST".

Response: Thanks for the suggestion. It has been revised.

Be consistent. Equ. or Equation ?

Response: Thanks for the careful check. We have changed "Equation" or "Equ." to "Eq." in our revised manuscript.

Figs. 2a and 2b. leave a space before and after "time series" in the title.

Response: Thanks for the suggestion. The Fig. 2 has been replotted.

References:

The references are not arranged exactly in the alphabetical order by the author's name.

Response: Thanks for the careful check. The references have been rearranged.