Replies to Referee RC2

Manuscript number: **EGUSPHERE-2024-2669**

Title: The Joint Effect of Mid-latitude Winds and the Westerly Quasi-Biennial Oscillation Phase on the Antarctic Stratospheric Polar Vortex and Ozone

2024

We thank the anonymous reviewer and the editor for your helpful comments which helped us greatly to improve our paper. We modified our paper according to the comments. Our replies are summarized as below:

In the original manuscript, we classified the WQBO into WQBO-Strong Polar Vortex (W-SPV) and WQBO-Weak Polar Vortex (W-WPV) according to the phase of the extratropical mode in July (Figure R1a). However, we realized that the two phases are misnamed, as a positive extratropical mode does not always lead to a stronger polar vortex, despite the strong correlation between them. In the revised manuscript, we renamed the positive and negative extratropic mode in July as Positive-Extratropic mode (Pos-Exmode) and Negative-Extratropic mode (Neg-Exmode) as in Figure R1b.

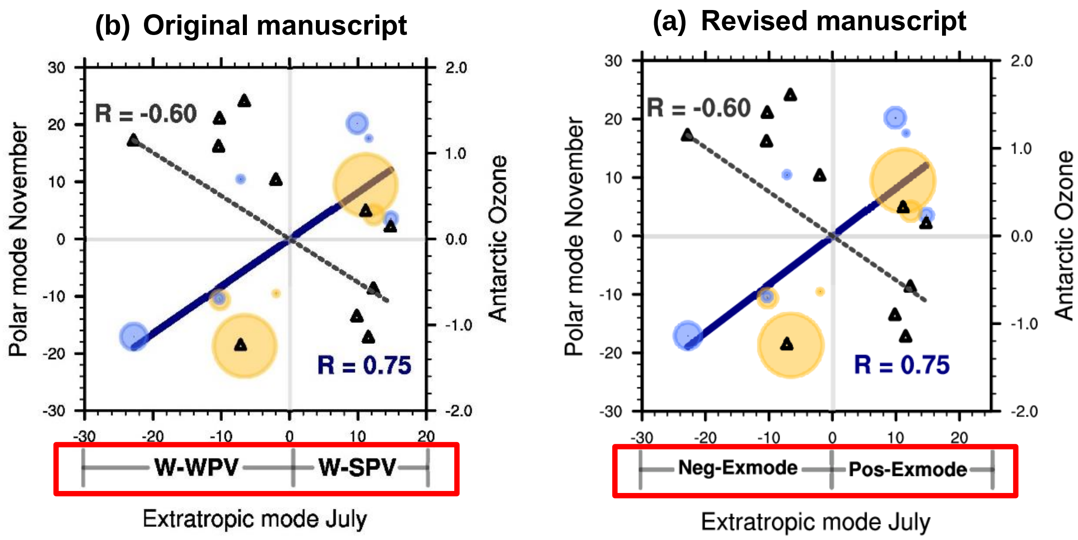

Figure R1. The corresponding time series for the extratropic mode and polar mode of Figure 3 in the manuscript. (a) The Figure 3c in the original manuscript. (b) The Figure 3c in the revised manuscript.

Summary

Using the reanalysis and model simulations, this study analyzes the possible impact of the subtropical stratospheric wind mode on the QBO-Southern Hemisphere stratospheric polar vortex. The authors find that the westerly winds in the subtropics can increase the correlation between the QBO and the polar vortex wind, while this relation is weak during the easterly winds in the subtropics. This finding is very interesting and important for seasonal forecast in the Arctic circulation and ozone. Therefore, I suggest to publish this paper with the following comments considered.

Specific comments

This study finds that the subtropical westerlies can increase the relationship between the WQBO and the strong polar vortex. However, this relationship is asymmetric. I meant that if the subtropical easterlies can increase the relationship between the EQBO and the weak polar vortex.

Response: Thank you for your comment. First, the QBO-polar vortex coupling between the easterly quasi-biennial oscillation phase (EQBO) and westerly quasi-biennial oscillation phase (WQBO) is inherently asymmetric. Figure R2 shows the probability distribution of the zonal-mean zonal wind at 60°S and 50 hPa in November. Compared to the black line, the green line shifts to the left, while the center position of the orange line aligns closely with the black line, suggesting that the EQBO has a greater influence on the Antarctic stratospheric polar vortex than the WQBO.

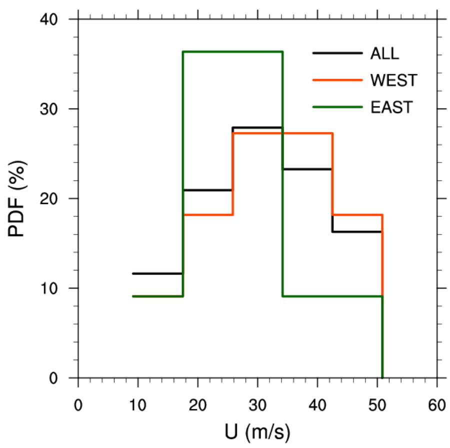

Figure R2. Probability distribution of 60°S zonal-mean zonal wind at 50 hPa in November during 1980−2022 (black line), WQBO (orange line), and EQBO (green line).

Furthermore, we agree that the relationship in our manuscript is also asymmetric between the WQBO and EQBO. As in the manuscript, we first show the regressed zonal-mean zonal wind in austral winter (from June to August) against the strength of the polar vortex in October and November during the EQBO. In EQBO, no uniform, statistically significant correlation pattern is observed throughout the winter in the upper stratospheric extratropical regions (Figures R3d−f), even with a shorter time lag (Figures R3a−c). Note that the most significant correlations appear in Figure R3c, where the polar vortex in October is related to the August zonal-mean zonal winds between 30°S−60°S in the upper stratosphere. This suggests that during the EQBO, the extratropic-polar connection to begin later, with the extratropical zonal wind positioned at higher latitudes. Given that, we replotted Figure 4 of the manuscript, but during the EQBO. Unlike in the WQBO, the extratropical mode in EQBO is calculated from the September zonal-mean zonal wind over 30°S−50°S and 1−70 hPa, with a correlation to the November Antarctic polar vortex reaching as high as 0.71. Thus, it's true that the relationship mentioned in our manuscript is asymmetric between the WQBO and EQBO.

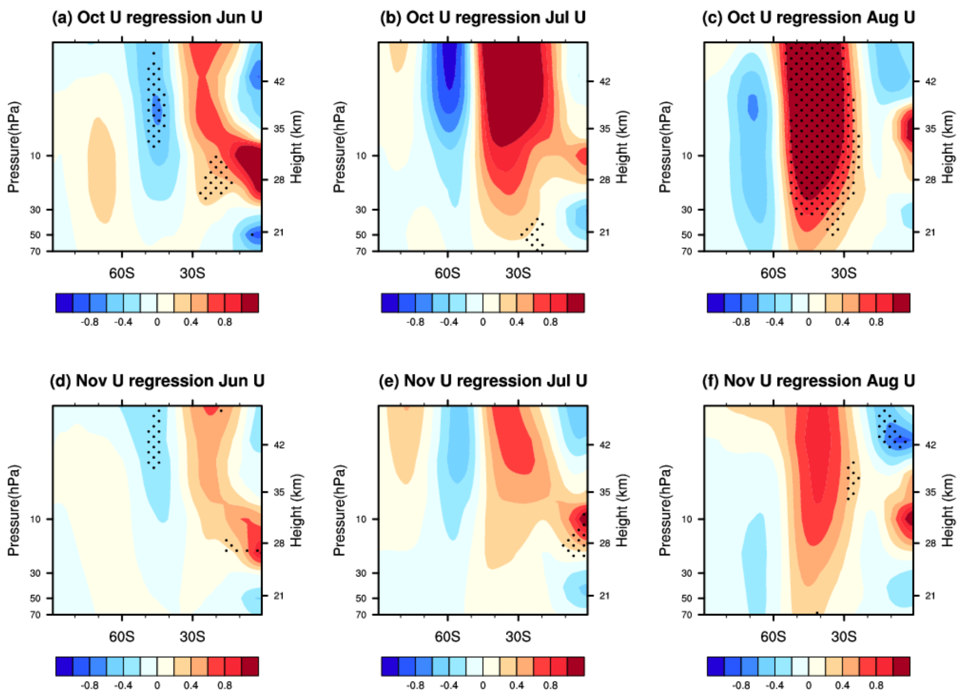

Figure R3. (a)−(c) Regression patterns of the zonal-mean zonal wind in (a) June, (b) July, and (c) August against the zonal-mean zonal wind at 60ºS and 70 hPa in October derived from the MERRA-2 reanalysis dataset. (d)−(f) Regression patterns of the zonal-mean zonal wind in (d) June, (e) July, and (f) August against the zonal-mean zonal wind at 60ºS and 70 hPa in November derived from the MERRA-2 reanalysis dataset. The shadings indicate that the regression coefficients are statistically significant at 95% confidence level.

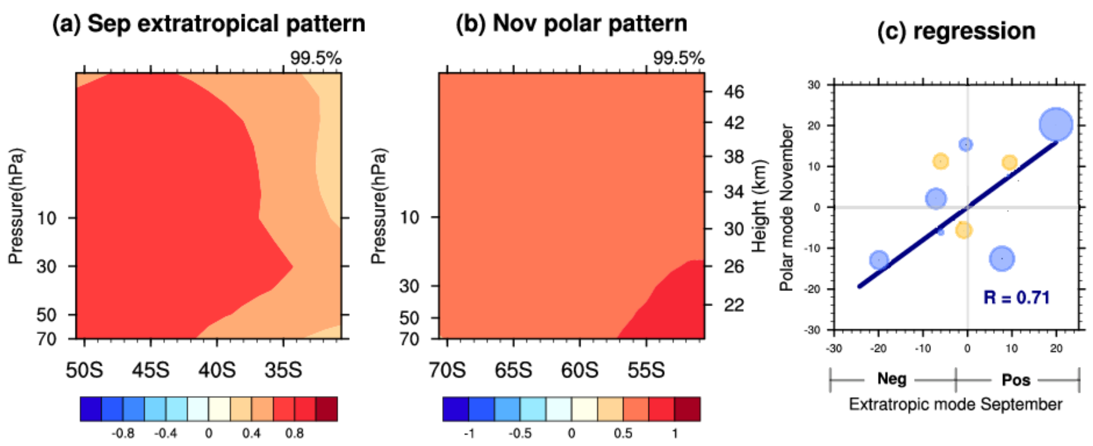

Figure R4. Spatial patterns for the first paired mode of the (a) monthly mean zonal-mean zonal wind over 30−50°S and 1−70 hPa in September, (b) zonal-mean zonal wind over 50°S−70°S and 1−70 hPa in November by the singular value decomposition (SVD) analysis during EQBO years, based on the MERRA-2 reanalysis dataset from 1980 to 2022. (c) The corresponding time series for the paired mode, with their correlation coefficient shown in the bottom right-hand corner. The solid blue line represents the linear regression of the extratropical mode and polar mode. The size and color of the circle markers in panel (c) are proportional to the Niño 3.4 index, with yellow dots indicating a positive Niño 3.4 index and blue dots indicating a negative Niño 3.4 index.

This study states that few studies focus on the relationship between QBO and the SH stratospheric polar vortex, and that the relation between them might be absent and non-existent. However, previous studies have reported the possible impact of QBO on the SH stratospheric polar vortex. The maximized response of the SH stratosphere to the QBO appears in boreal spring, not in winter (Rao et al. 2023a, b).

Response: Thank you for your comment. We agree the original phrasing was unclear, and we have revised the sentence as follows.

"In the Southern Hemisphere (SH), upward-propagating planetary waves are weak due to the weaker thermal contrast between land and sea. Consequently, the QBO-vortex coupling, which is closely related to planetary waves, has received less attention than those in the Northern Hemisphere (Garcia and Solomon, 1987; Lait et al., 1989; Baldwin and Dunkerton, 1998; Naito, 2002; Hitchman and Huesmann, 2009; Yamashita et al. 2018; Rao et al., 2023a, 2023b)."

Furthermore, in addition to the Naito et al. (2002) and Anstey et al. (2014), two other studies have been incorporated into the introduction.

"Yamashita et al. (2018) examined the influence of the QBO on SH extratropical circulation from austral winter to early summer using a multiple linear regression

approach. Their findings suggest that the QBO-SH polar vortex connection operates through two distinct pathways: the mid-stratospheric pathway, which tends to suppress the propagation of planetary waves into the stratosphere during WQBO, and the low-stratospheric pathway, which tends to enhance upward planetary waves in EQBO. The QBO-SH polar vortex connections established by Yamashita et al. (2018) are statistically significant. However, in QBO-resolving models from phases 5/6 of the Coupled Model Intercomparison Project (CMIP5/6), fewer than half of the General Circulation Models (GCM) successfully reproduce a weakened SH polar vortex during EQBO (Rao et al., 2023a). Furthermore, they also suggest that even the high-skill models capture only about 30% of the observed deceleration in westerlies during the EQBO. Although previous studies have revealed the potential relationship and mechanisms linking the QBO with the Antarctic stratospheric polar vortex, the weak statistical correlation between them and the limited performance of GCMs indicate that the QBO-vortex coupling in the SH is not jet fully understood."

This study used model simulation by nudging methods. However, the method does not describe the necessity of the experiment. All figure captions should also mention if the results are based on ERA5 or ERA5. If the stratosphere is nudging, what can we learn from the experiments with t this study still focusing on the stratospheric variability?

Response: Thank you for your comment. All figure captions have been verified, and the data source have been clearly specified.

The nudging simulation allows us to create additional WQBO ensemble members with varying initial conditions, reducing noise from the initial fields. In these model simulations, only tropical meteorological fields are nudged, while the other stratospheric regions evolve freely. This setup enables us to interpret the resulting extratropical patterns as responses to the WQBO signals in the tropical stratosphere (Figure R5).

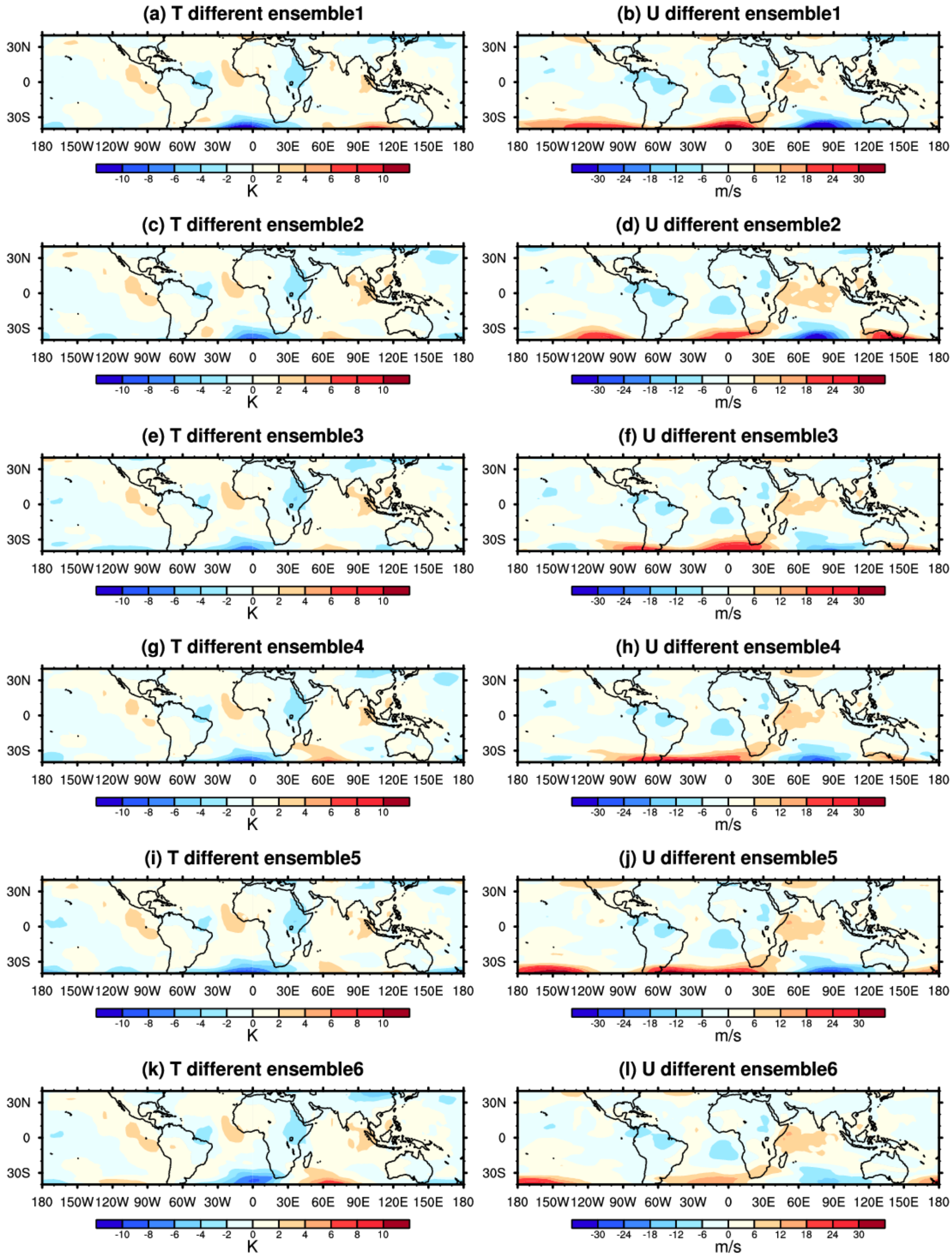

Figure R5. (a), (c), (e), (g), (i), and (k) Difference in temperature between the CESM model simulation and JRA55 reanalysis dataset at 50 hPa on 1 September 2021 from different ensembles. (b), (d), (f), (h), (j), and (l) Difference in zonal wind between the CESM model simulation and JRA55 reanalysis dataset on 1 September 2021.

Because the Whole Atmosphere Community Climate Model (WACCM) cannot reproduce a realistic QBO and instead produces weak easterlies in the equatorial lower stratosphere. Therefore, similar to most studies on the QBO, the equatorial zonal winds are relaxed toward idealized wind patterns (Matthes et al., 2010; Wang et al., 2022; Luo et al., 2024; Zhang et al., 2024). Zhang et al. (2024) used the QBO-nudging simulation to analyze precipitation in East Asia. Their findings further validate the effectiveness of nudging simulations for analyzing QBO influences on other processes. We used the same experiments derived from Zhang et al. (2024).

Reference

Luo, J. L. et al.: The impact of the QBO vertical structure on June extreme high temperatures in South Asia. npj Clim. Atmos. Sci., 7, 236, doi: 10.1038/s41612-024-00791-2, 2024

Matthes, K. et al.: Role of the QBO in modulating the influence of the 11 year solar cycle on the atmosphere using constant forcings. J. Geophys. Res., 115, D18110, doi: 10.1029/2009JD013020, 2010.

Wang, W. K., Hong, J., Shangguan, M., Wang, H. Y., Jiang W. and Zhao S. Y.: Zonally asymmetric influences of the quasi-biennial oscillation on stratospheric ozone, Atmos. Chem. Phys., 22, 13695–13711, doi: 10.5194/acp-22-13695-2022, 2022.

Zhang, R. H., Zhou W., Tian, W. S., Zhang, Y., Zhang, J. X. and Luo, J. L.: A stratospheric precursor of East Asian summer droughts and floods, Nat. Commun., 15, 247, doi: 10.1038/s41467-023-44445-y, 2024.

L15: anomalous zonal-mean zonal wind => zonal-mean zonal wind anomalies

Response: Thank you for the careful check. It has been revised.

L21: References are required for this sentence.

Response: Thank you for your comment. We have revised this sentence as:

"The quasi-biennial oscillation (QBO) is a dominant mode of interannual variability in the tropical stratosphere (Lindzen and Holton 1968; Andrews and McIntyre 1976; Baldwin et al. 2001; Anstey and Shepherd, 2014; Rao et al., 2019; 2020a; 2023a)."

L22: wind … descend => wind … descends

Response: Thank you for the careful check. It has been revised.

L31: Arctic ozone => Arctic ozone and water vapor (https://doi.org/10.1016/j.wace.2023.100627)

Response: Thank you for your comment. We have added 'water vapor'.

"This QBO-induced changes in the Arctic stratospheric polar vortex can further influence the distribution of Arctic ozone and water vapor (Wang et al., 2022; Lu et al., 2023)."

L33: It depends on the timescale concerned. On the interannual timescale, the chemical processes are weaker than transport.

Response: Thank you for your comment. This sentence has been written as:

"Zhang et al. (2021) revealed that dynamical processes contribute more to the Arctic ozone-QBO connection than chemical processes, although the impact of chemical processes on the Arctic ozone QBO signal is not negligible."

L36: less thermal contrast => weaker thermal contrast

Response: Thank you for the careful check. It has been revised.

L38, L41-44: Two recent publications mentioned the impact of QBO on the Southern Hemisphere stratosphere.

Response: Thank you for your comment. The two recent studies have been added in the revised manuscript.

"In the Southern Hemisphere (SH), upward-propagating planetary waves are weak due to the weaker thermal contrast between land and sea. Consequently, the QBO-vortex coupling, which is closely related to planetary waves, has received less attention than those in the Northern Hemisphere (Garcia and Solomon, 1987; Lait et al., 1989; Baldwin and Dunkerton, 1998; Naito, 2002; Hitchman and Huesmann, 2009; Yamashita et al. 2018; Rao et al., 2023a, 2023b)."

"Yamashita et al. (2018) examined the influence of the QBO on SH extratropical circulation from austral winter to early summer using a multiple linear regression approach. Their findings suggest that the QBO-SH polar vortex connection operates through two distinct pathways: the mid-stratospheric pathway, which tends to delay the downward evolution of the polar-night jet during WQBO, and the low-stratospheric pathway, which tends to enhance upward planetary waves in EQBO. The QBO-SH polar vortex connections established by Yamashita et al. (2018) are statistically significant. However, in QBO-resolving models from phases 5/6 of the Coupled Model Intercomparison Project (CMIP5/6), fewer than half of the General Circulation Models (GCM) successfully reproduce a weakened SH polar vortex during EQBO (Rao et al., 2023a). Furthermore, they also suggest that even the high-skill models capture only about 30% of the observed deceleration in westerlies during the EQBO. Although previous studies have revealed the potential relationship and mechanisms linking the QBO with the Antarctic stratospheric polar vortex, the weak statistical correlation between them and the limited performance of GCMs indicate that the QBO-vortex coupling in the SH is not jet fully understood."

L48: It is too certain to say so.

Response: Thank you for your comment. We agree that the phrase 'the only region' in the original manuscript seems too certain. We have revised the sentence as follows:

"Wang et al. (2022) suggested that the Antarctic total column ozone (TCO) shows no significantly respond to the QBO signal (Figure 2 in Wang et al., 2022)."

L50: The QBO of which period varies irregularly in the range from 17 to 38 months is considered as a reliable predictor => The QBO period varies irregularly in the range from 17 to 38 months, which is considered as a reliable predictor

Response: Thank you for the careful check. It has been revised.

L70: Here it is worth mentioning that the QBO index at 20 hPa is used, different from studies for Northern Hemisphere.

Response: Thank you for your comment. This sentence has been written as follows.

"Typically, when tropical stratosphere winds near 50 hPa are used to define the QBO phase, the NH stratospheric polar vortex during winter tends to strengthen during the WQBO and weaken during the EQBO (Baldwin et al. 2001; Anstey and Shepherd, 2014; Anstey et al., 2022). In the SH, the Antarctic stratospheric polar vortex shows responses to the tropical winds around 20 hPa (Baldwin and Dunkerton 1998; Baldwin et al., 2001; Baldwin and Dunkerton 1998; Anstey et al., 2022; Rao et al., 2023b). Therefore, this study uses the standardized zonal-mean zonal wind averaged over 10°S−10°N at 20 hPa to define the QBO phase."

L74: Monthly => monthly

Response: Thank you for the careful check. It has been revised.

L95: mean stream function => mean mass stream function

Response: Thank you for the careful check. It has been revised.

L100: phi is geopotential or potential height? Please check.

Response: Thank you for your comment. Ψ is the geopotential height scaled by the Coriolis parameter, which is defined as follows (Harnik and Lindzen, 2001):

$$\Psi = \phi / f \quad \textbf{(R1)}$$

Reference

Harnik, N. and Lindzen, R. S.: The effect of reflecting surfaces on the vertical structure and variability of stratospheric planetary waves, J. Atmos. Sci., 58, 2872–2894, doi: 10.1175/1520-0469(2001)058<2872:TEORSO>2.0.CO;2, 2001.

L107, 111: dm, what is the meaning of m?

Response: Thank you for your comment. The $\int [s] dm$ is defined as $\int_z \int_y \int_x s\rho \, dx \, dy \, dz$ (Hu et al., 2004), and the ρ is the air density. This point has been clarified in the revised manuscript.

"The $\int [s] dm$ is defined as $\int_z \int_y \int_x s\rho_0 \, dx \, dy \, dz$."

Reference

Hu, Q., Tawaye, Y. and Feng, S.: Variations of the Northern Hemisphere Atmospheric Energetics: 1948–2000, J. Climate, 17, 1975–1986, doi: 10.1175/1520-0442(2004)017<1975:VOTNHA>2.0.CO;2, 2004.

L120: ’’ denotes meridional average? I did not see ’’ in all equations.

Response: Thank you for your comment. The $''$ represents departure from meridional average, and is used in calculation of the mean available potential energy (PM).

$$\mathrm{PM} = \frac{c_p}{2} \int \gamma [< T >]''^2 \, dm \quad \textbf{(R2)}$$

L125: 1.9*2.5 => 0.95*1.25

Response: Thank you for your comment. We have examined the horizonal resolution of the model, which is 1.9° × 2.5°.

L148: several months => Please tell the specific number.

Response: Thank you for your comment. This sentence has been rewritten as:

"The QBO-SH polar vortex connection emerges in July and persists until austral late spring, with the effect peaking in November (i.e., the influence of the July QBO on the polar vortex peaks four months later, the influence of the August QBO peaks three months later, and so on). This result is consistent with the previous studies (Baldwin and Dunkerton, 1998; Yamashita et al., 2018)."

L151: influence => influences

Response: Thank you for the careful check. It has been revised.

L158: This relation indeed exists, but the maximum response of the polar vortex to QBO is in austral spring.

Response: Thank you for your comment. This sentence has been written as:

"The WQBO in winter (QBO index in July greater than 1) does not consistently lead to a stronger zonal-mean zonal wind in polar regions in spring, and the correction between them is only 0.23. These results suggest that the direct impact of the QBO on the Antarctic polar vortex is weak."

L166: measure => depict

Response: Thank you for the careful check. It has been revised.

L168: and polar => and polar regions.

Response: Thank you for the careful check. It has been revised.

L239: negative anomalous temperature => negative temperature anomalies

Response: Thank you for the careful check. It has been revised.

L255: exhibit a … anomalies => remove a

Response: Thank you for the careful check. It has been revised.

L276: as a results => as a result

Response: Thank you for the careful check. It has been revised.

L356: moths => months?

Response: Thank you for the careful check. It has been revised.

L379: It is unknow which figure are based on the sensitivity experiments.

Response: Thank you for your comment. Figure R6 (Figure 8 in the manuscript) shows the CESM model simulation results. The QBO nudging simulations with varying initial fields support our findings that the extratropical mode plays an important role in establishing the relationship between the WQBO and the Antarctic stratospheric polar vortex. In the revised manuscript, all figure captions have been verified, and data sources are now clearly specified.

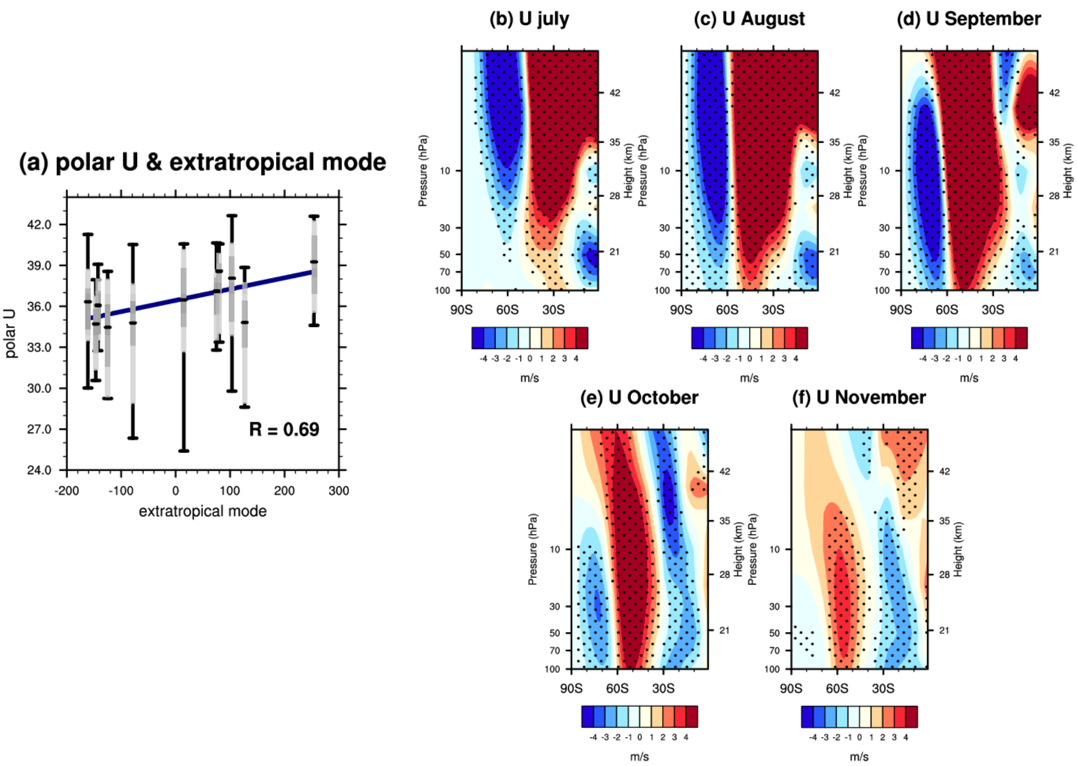

Figure R6. (a) The zonal-mean zonal wind at 60ºS and 100 hPa in November is

plotted against the extratropical mode's PC in July, derived from the 20 ensembles of CESM simulation. The boxplot describes a summary of these ensembles. The light grey box spans from the lower dectile to the upper dectile, and the dark grey spans the lower quartile to upper quartile. The lines inside the dark grey box marks the median zonal wind. The lower and upper whiskers indicate the minimum and maximum zonal wind among the 20 ensembles. Additionally, the blue line represents the linear fit between the extratropical mode and the median zonal wind, with their correlation coefficient displayed in the bottom right-hand corner. (b)−(f) Composite differences in zonal-mean zonal wind from July to November between the Pos-Exmode and Neg-Exmode according to CESM simulations. The dotted regions mark the differences between the Pos-Exmode and Neg-Exmode are statistically significant at the 95% confidence level.

L386: anomalous … wind => … wind anomalies

Response: Thank you for the careful check. It has been revised.