Replies to Referee RC1

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.

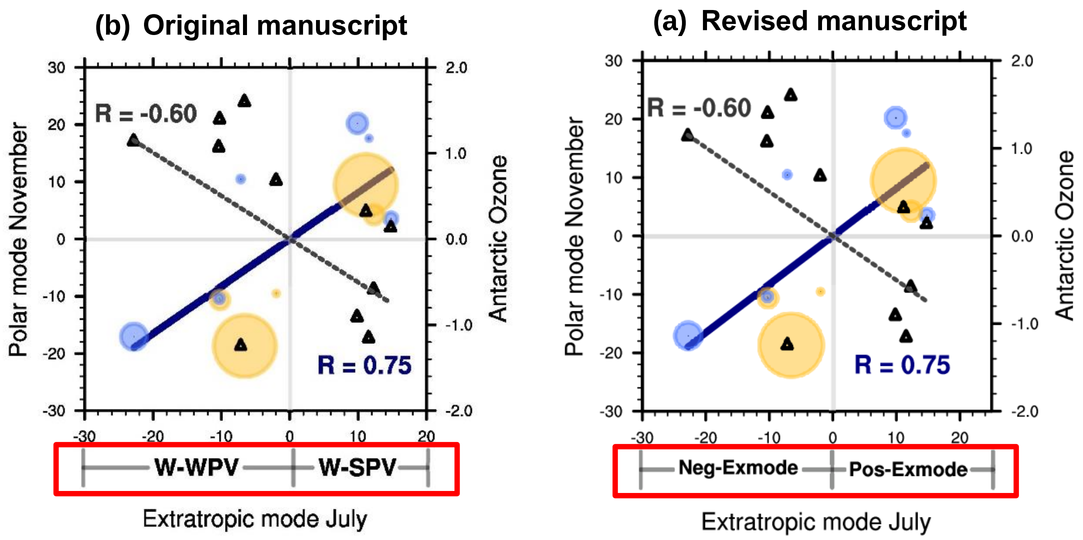

Figure R1. The corresponding time series for the extratropic mode and polar mode of Figure 3 in the manuscript. (a) The Figure 3c in the original manuscript. (b) The Figure 3c in the revised manuscript.

This paper establishes a robust connection between the QBO signal in winter and the stratospheric polar vortex in spring with a time-lag of five months. Their results indicated that zonal-mean zonal winds in the mid-latitude upper stratosphere play a crucial role in facilitating the tropic-polar connection in Southern Hemisphere.

Specifically, during WQBO, the positive zonal-mean zonal winds anomalies at 20°S−40°S in the upper stratosphere in July can lead to a stronger Antarctic stratospheric polar vortex and lower ozone concentrations in November. This finding on predicting the Antarctic polar vortex and ozone in spring could be of broad interest, and the authors have presented a comprehensive body of work on it. Overall, this paper presents an interesting and convincing and well-written analysis. I think this study would be of interest to the readership Atmospheric Chemistry and Physics and recommend its publication after addressing the comments listed below.

General comments:

In the introduction, the authors mentioned that most researches focus on the QBO-polar connection in the Northern Hemisphere (NH), where the upward-propagating planetary waves are strong. A more detailed explanation of the underlying mechanisms, along with a discussion of whether this connection in the NH is robust, would strengthen the introduction. I think this would offer readers more useful information about why there is less attention on the QBO-polar connection in the Southern Hemisphere.

Response: Thank you for your comment. A detailed explanation of the Holton-Tan effect has been added in the revised manuscript.

"During the westerly QBO phase (WQBO), the zero-wind line of the zonal-mean zonal wind shifts equatorward, causing planetary wave to be reflected away from high latitudes. This dynamic is expected to strengthen the polar vortex by reducing wave-driven disturbances in the polar region. Consequently, the Arctic stratospheric polar vortex and the Brewer-Dobson circulation (hereafter referred to as B-D circulation) tend to be stronger on average during the WQBO compared to the easterly QBO phase (EQBO). Additionally, Garfinkel et al. (2012) proposed that the secondary meridional circulation induced by the EQBO also plays a crucial role in the Arctic stratosphere. This secondary circulation restricts the propagation of subpolar Rossby waves into the subtropics, resulting in more wave breaking closer

to the pole.”

The study defines the QBO phase using zonal-mean zonal wind at 20 hPa. However, I noticed that most researches define the QBO as being in its easterly (westerly) phase using the zonal mean zonal wind at 50 hPa. It would be very instructive to show why defining the QBO phase at 20 hPa is reasonable for establishing the QBO-polar connection in the SH.

Response: Thank you for your comment. In the original manuscript, we discussed the reason why a single-level wind (20 hPa) has been used to select the WQBO and EQBO years. To clarify further, the empirical orthogonal function (EOF) analysis is applied to the tropical zonal-mean zonal wind, averaged over 10°S–10°N from 10 hPa to 70 hPa (following Randel et al., 1999; Anstey et al., 2010; Rao and Ren, 2018). The first EOF mode depicts the in-phase changes in equatorial stratospheric zonal wind from the lower to the upper stratosphere (black line in Figure R2a), accounting for 56.04% of the total variance and showing the maximum correlation with the single-level equatorial wind at 20–30 hPa. The second EOF mode represents the contrasting variations between the lower and upper stratosphere (black line in Figure R2b), and it agrees well with the equatorial wind at 50 hPa (blue line in Figure R2b) variation. However, the second EOF mode explains only about 30% of the total variance, suggesting that the first EOF mode-like equatorial wind at 20–30 hPa serves as a good indicator of the QBO phase.

Additionally, years in WQBO and EQBO are selected according to the equatorial wind at 20 and 30 hPa, as shown in Table R1. Note that the years identified by the 20 hPa zonal wind largely overlap with those at 30 hPa, except for 2022. Therefore, we use 20 hPa equatorial wind to define the QBO phase, consistent with previous studies (Baldwin et al., 2001; Naito, 2002; Rao et al., 2020).

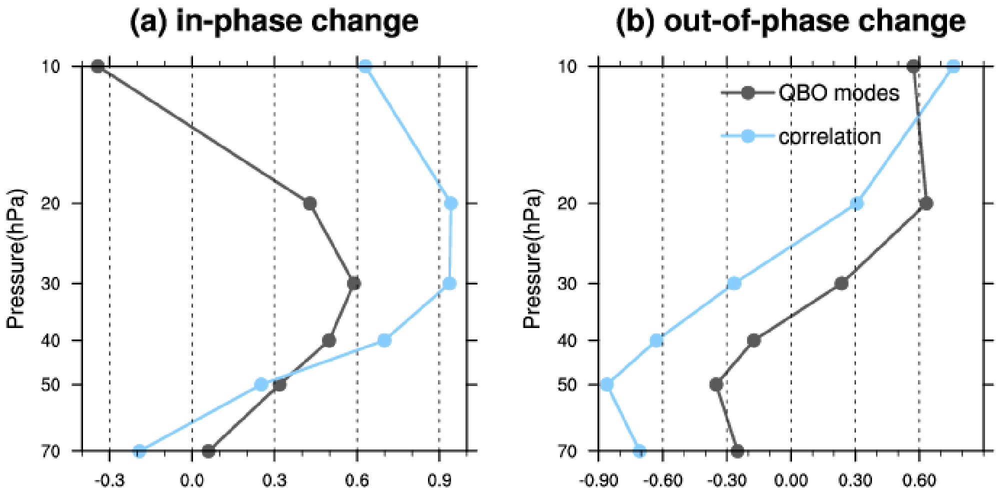

Figure R2. We first obtain the first two principal components (PCs) of the monthly mean zonal-mean zonal wind, averaged over 10°S–10°N from 10 hPa to 70 hPa in July, through empirical orthogonal function (EOF) analysis. (a) The vertical structure of the in-phase QBO mode (black line), and the correlation between this PC and the tropical zonal-mean zonal wind at different levels (blue line). (b) Same as panel (a), but for the out-of-phase mode.

Table R1. Years categorized as WQBO and EQBO are selected based on the tropical zonal wind at 20 hPa and 30 hPa.

Level	WQBO
20 hPa	1980, 1985, 1990, 1997, 2004, 2006, 2008, 2013, 2015, 2016, 2022
30 hPa	1980, 1985, 1990, 1995, 1997, 1999, 2002, 2004, 2006, 2008, 2013, 2015, 2016, 2019

Reference

Anstey, J. A., Shepherd, T. G. and Scinocca, J. F.: Influence of the quasi-biennial oscillation on the extratropical winter stratosphere in an atmospheric general circulation model and in reanalysis data, J. Atmos. Sci., 67, 1402–1419, doi: 10.1175/2009JAS3292.1, 2010.

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K, Haynes, P. H., Randel,

W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquardt, C., Sato, K. and Takahashi, M.: The quasi-biennial oscillation, Rev. Geophys., 39, 179–229, doi: 10.1029/1999RG000073, 2001.

Naito, Y.: Planetary wave diagnostics on the QBO effects on the deceleration of the polar-night jet in the southern hemisphere, J. Meteor. Soc. Japan, 80, 985–995, doi: 10.2151/JMSJ.80.985, 2002.

Rao, J., Garfinkel, C. I. and White, I. P.: Impact of the Quasi-Biennial Oscillation on the Northern Winter Stratospheric Polar Vortex in CMIP5/6 Models, J. Climate, 33, 4787–4813, doi: 10.1175/JCLI-D-19-0663.1, 2020.

Yamashita, Y., Naoe, H., Inoue, M. and Takahashi, M.: Response of the Southern Hemisphere Atmosphere to the Stratospheric Equatorial Quasi-Biennial Oscillation (QBO) from Winter to Early Summer, J. Meteorol. Soc. Jpn., 96, 6, 587−600, doi: 10.2151/jmsj.2018-057, 2018.

The correlation between the winter extratropical mode and the polar vortex reaches 0.75 during WQBO. It seems the winter extratropical mode could serve as a good predictor of the spring Antarctic stratospheric polar vortex. Additionally, in Figure 3c, a positive extratropical mode in July usually corresponds to a strong polar vortex. Would it be possible that the author uses these relationships to ‘predict’ the strength of the Antarctic polar vortex from 1950 to 1979 using the ERA5 reanalysis?

Response: Thank you for your comment. Figure R3 shows the ‘predicted’ polar vortex during the WQBO phase from 1950 to 1979. Of the seven samples identified as WQBO, six are successfully classified to the strong or weak polar vortex by the extratropical mode, supporting the robustness of the mechanisms discussed in the original manuscript.

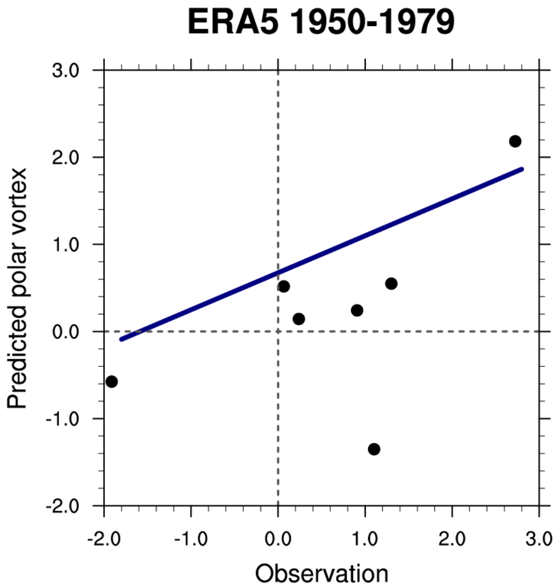

Figure R3. The standardized zonal-mean zonal wind at 60°S and 70 hPa plotted against the predicted polar vortex by the extratropical mode during the WQBO from 1950 to 1979 derived from ERA5 reanalysis dataset. The blue line represents the linear regression of the observation and predicted polar vortex.

Specific comments:

Line 25 Please specify how QBO modify the upward-propagating planetary waves.

Response: Thank you for your comment. The following sentence has been added to the revised manuscript.

"During the westerly QBO phase (WQBO), the zero-wind line of the zonal-mean zonal wind shifts equatorward, causing planetary wave to be reflected away from high latitudes. This dynamic is expected to strengthen the polar vortex by reducing wave-driven disturbances in the polar region. Consequently, the Arctic stratospheric polar vortex and the Brewer-Dobson circulation (hereafter referred to as B-D circulation) tend to be stronger on average during the WQBO compared to the easterly QBO phase (EQBO). Additionally, Garfinkel et al. (2012) proposed that the secondary meridional circulation induced by the EQBO also plays a crucial role in the Arctic stratosphere. This secondary circulation restricts the propagation of subpolar Rossby waves into the subtropics, resulting in more wave breaking closer

to the pole."

Line 51 The QBO is only considered as a predictor of the Arctic stratospheric polar vortex and the near-surface climate in the NH. Please clarify this point.

Response: Thank you for your comment. This sentence has been rewritten in the revised manuscript.

"The QBO period varies irregularly in the range from 17 to 38 months, which is considered as a reliable predictor of the stratospheric polar vortex, and further the near-surface climate and weather in the NH (Baldwin and Dunkerton, 2001; Zhang et al., 2020; Tian et al., 2023)."

Line 74 Monthly to monthly

Response: Thank you for your comment. Corrected.

Line 77 what is the vertical range being considered?

Response: Thank you for your comment. The vertical range of the SVD analysis has been clarified in the revised manuscript.

"The SVD analysis is performed between the zonal-mean zonal wind at latitudes ranging from 0° to 40°S and 1−70 hPa in July (extratropical mode) and the zonal-mean zonal wind at latitudes ranging from 50° to 70°S and 1−70 hPa in November (polar mode)."

Line 96 Why not use the traditional refraction index to diagnose the wave-propagation in the stratosphere?

Response: Thank you for your comment. First, note that from July to August, the difference in horizontal planetary wave between the Pos-Exmode and Neg-Exmode leads to anomalous E-P flux divergence (Figures 4f−g in the revised manuscript). Therefore, we display the meridional components of the refraction index (RI) in Figures 6k−l of the manuscript.

Secondly, Figure R4 shows the difference in traditional RI between the Pos-Exmode and Neg-Exmode in July. Similar to the meridional components of the refraction index, there are negative RI anomalies between 55°S and 65°S in the upper stratosphere, suggesting that the refraction index used in the manuscript is appropriate for investigating the wave propagation environment.

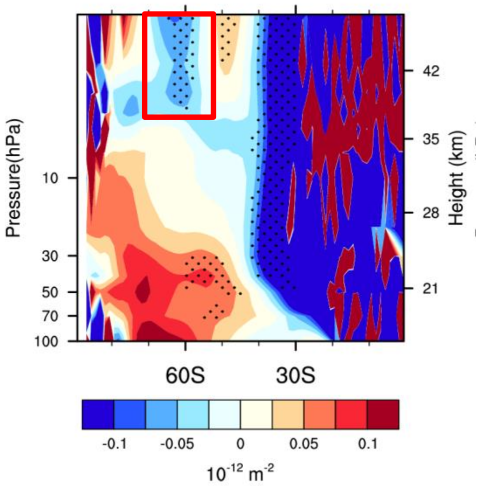

Figure R4. Composited difference in traditional RI between the Pos-Exmode and Neg-Exmode in July derived from MERRA-2 reanalysis dataset.

Line 102 The word size of the equation (7) is too large. Please correct.

Response: Thank you for your comment. Corrected.

Line 136 I note that in the CESM, the stratospheric conditions are nudged to the JRA-55 reanalysis. Why is the model forced using different types of reanalysis data?

Response: Thank you for your comment. We agree that discrepancies may exist between different reanalysis dataset, and validating the results across multiple datasets can enhance their robustness. First, we present the WQBO years selected based on the MERRA-2 and JRA55 reanalysis datasets in Table R2. The WQBO years show strong consistence between these two datasets.

Secondly, we reprinted Figure 3 of the manuscript using the JRA55 reanalysis dataset (Figure R5). This analysis similarly shows a strong correlation between

the extratropic mode in July and the Antarctic polar vortex in late austral spring, suggesting that the conclusions in the original manuscript are not influence by the choice of reanalysis dataset. Additionally, in the original manuscript, we clarified the use of different reanalysis datasets, and the consistency of the results across both datasets further demonstrates the robustness of our findings.

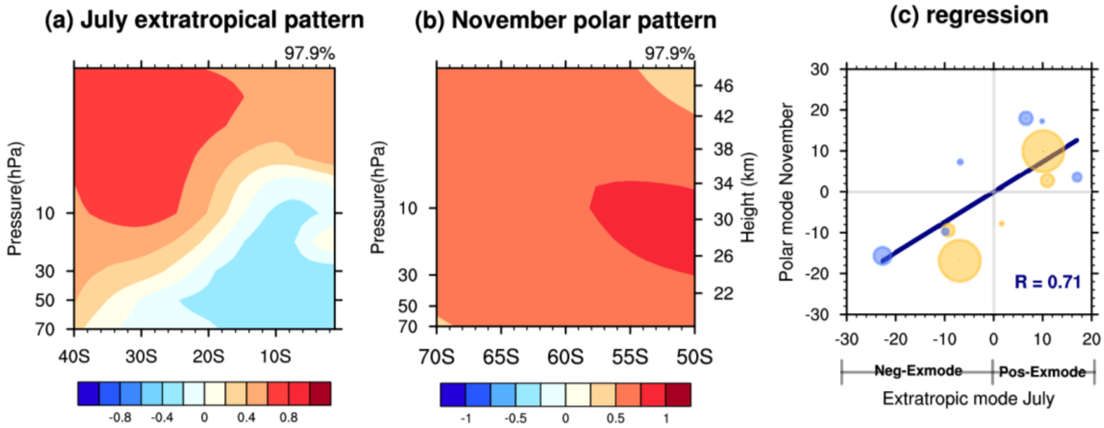

Figure R5. Same as Figure 3 of the manuscript, but it derived from JRA55 reanalysis datasets.

Table R2. Years categorized as WQBO based on the MERRA-2 and JRA55 reanalysis datasets.

Dataset	WQBO
MERRA-2	1980, 1985, 1990, 1997, 2004, 2006, 2008, 2013, 2015, 2016, 2022
JRA55	1980, 1985, 1990, 1997, 2004, 2006, 2008, 2013, 2015, 2016, 2022

Figure 1b It seems no apparent connection between the QBO in July and the Antarctic stratospheric polar vortex in austral spring. However, in the introduction, how previous studies have shown that the QBO can modulate the Antarctic polar vortex during austral spring?

Response: Thank you for your comment. Some of the previous studies used the composite analysis to explore the connection between the QBO and the Antarctic

stratospheric polar vortex (Baldwin and Dunkerton, 1998; Anstey and Shepherd, 2014). However, their composite analysis indicated only a slight response of the vortex to the QBO phase, and no statistical test to confirm these findings. Here, we also present the composited difference in zonal-mean zonal wind between the WQBO and EQBO. Even when using the November QBO index to estimate stratospheric Antarctic polar vortex for the same month, the significant difference in zonal-mean zonal wind between the WQBO and EQBO remains limited in extent, centered around 60°S at 100 hPa (Figure R6a). When the QBO signal leads to the stratospheric Antarctic polar vortex for almost five months, there is no significant difference in zonal-mean zonal wind between the WQBO and EQBO (Figure R6b).

However, 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 results are statistically significant. Thus, the mechanism in previous studies may not be adequate to explain the entirety of the extratropical response in the SH.

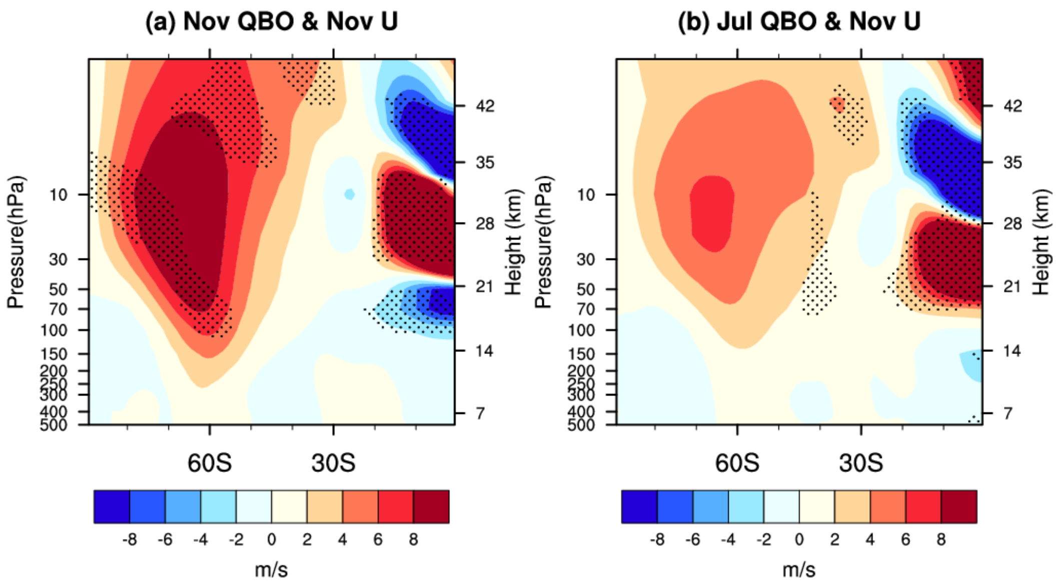

Figure R6. (a) Composite differences in zonal-mean zonal wind anomalies in November between the WQBO and EQBO according to MERRA-2 reanalysis

dataset from 1980 to 2022. The phase of QBO is defined by using equatorial wind data in November. (b) Same as panel (a), but the phase of QBO is defined by using equatorial wind data in July. The dotted regions mark the differences in zonal-mean zonal wind are statistically significant at the 95% confidence level.

Figures 3a and 3b The first paired mode explains 98.2% of the total variance. How is it possible for the first mode to account for nearly all of the total variance?

Response: Thank you for your comment. Figure R7 presents the July extratropical pattern and the difference in zonal-mean zonal wind between the Pos-Exmode and Neg-Exmode. The two patterns are nearly identical, indicating that the extratropical pattern captures most of the information on the zonal-mean zonal wind distribution during the WQBO. Additionally, note that the November polar patter shown in Figure 3b of the manuscript represents the Antarctic polar vortex, the dominant feature of the polar region in austral spring. Consequently, the first paired mode accounts for nearly all of the total variance.

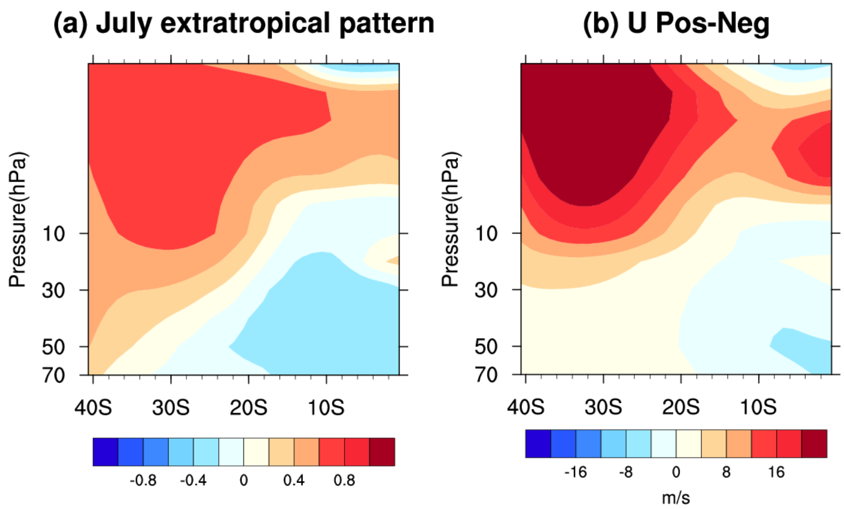

Figure R7. (a) Spatial patterns for the first paired mode of the (a) monthly mean zonal-mean zonal wind over 0−40°S and 1−70 hPa in July by the singular value decomposition (SVD) analysis during WQBO years, based on the MERRA-2 reanalysis dataset from 1980 to 2022. (b) Composite differences in the zonal-mean zonal wind anomalies in July between the Pos-Exmode and Neg-Exmode according to MERRA-2 reanalysis dataset.

Figure 4 ‘horizontal component unit: 107 kg s−2; vertical component unit: 105 kg s−2’. Please correct the units.

Response: Thank you for your comment. Corrected.

Line 249 W* to w*

Response: Thank you for your comment. Corrected.

Line 306 ‘25 ensembles’ to 20 ensembles

Response: Thank you for your comment. Corrected.

Line 381 positive anomalies in the zonal-mean zonal wind -> positive zonal-mean zonal wind anomalies

Response: Thank you for your comment. Corrected.

Line 400 ‘EQBO has a greater influence on the stratospheric polar vortex than the WQBO’ Please explain.

Response: Thank you for your comment. Figure R8 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.

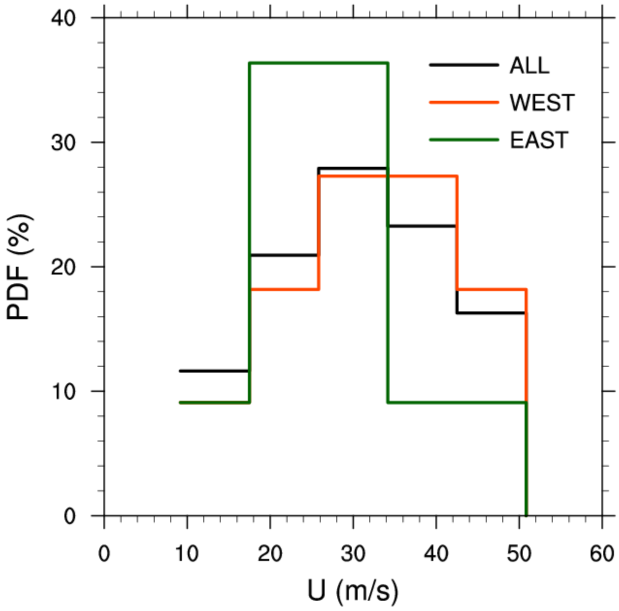

Figure R8. Probability distribution of 60°S zonal-mean zonal wind at 50 hPa in November during 1980−2022 (black line), WQBO (orange line), and EQBO (green line).