Response to Referee's Comments

Manuscript No.: egusphere-2025-955

Title: The Impact of the Stratospheric Quasi-Biennial Oscillation on Arctic Polar Stratospheric Cloud Occurrence

Author(s): Douwang Li[1], Zhe Wang[1], Siyi Zhao[1], Jiankai Zhang[1]*, Wuhu Feng[2,3], Martyn P. Chipperfield[3,4]

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Summary of revision in manuscript

We thank very much the three reviewers for their helpful comments. We have modified our manuscript based on the comments and suggestions, which have greatly improved our paper and made it more informative. Our point-by-point replies are summarized below:

1. We acknowledge the reviewer's view that the composited PSC anomalies between the WQBO and EQBO phases may not solely result from QBO forcing. To better isolate QBO-induced PSC anomalies, we performed ensemble sensitivity experiments using the CESM model with QBO forcing. The results support the conclusion that PSC area is generally larger during the WQBO phase than during the EQBO phase.

2. As suggested, we have divided Section 3 into two subsections to improve clarity.

3. We have compared MIPAS PSC observations (2002–2012) with CALIPSO and SLIMCAT. The three datasets exhibit consistent interannual variability in PSCs, which strengthens the credibility of our conclusions.

4. Some sentences have been rephrased and the grammar has been improved.

Response to Comments of Reviewer #2

General comments:

This manuscript, "The impact of the Stratospheric Quasi-Biennial Oscillation on Arctic Polar Stratospheric Occurrence", by Li et al. investigates how the QBO modulates Arctic PSC formation and, by extension, ozone depletion processes. The paper addresses a relatively underexplored but important linkage between QBO phase and PSC variability using satellite observations and SLMICAT simulations, and separates the roles of temperature, H_2O and HNO_3, via sensitivity experiments. It is topical given the implications for Arctic ozone recovery.

Specific comments:

1. My major concern lies with the sensitivity experiments. While the use of composites to assess QBO-related anomalies is methodologically reasonable, it remains unclear whether the observed changes in temperature (T), water vapor (H_2O), and nitric acid (HNO_3) are causally induced by the QBO alone.

In reality, the anomalies during WQBO/EQBO phases are influenced by multiple factors, and not solely by the QBO. Thus, attributing the entire composite difference to QBO forcing may overestimate its impact. I recommend that the authors address how they isolate QBO-specific variability from other confounding influences (e.g., ENSO, solar variability, volcanic aerosols).

If a full isolation is not feasible with the current dataset, the authors should clearly acknowledge this limitation and discuss the potential implications on the interpretation of their sensitivity results.

Response: Thank you for your constructive comment. We agree that other factors such as ENSO, solar variability, and volcanic aerosols may also influence the observed changes in temperature (T), water vapour (H_2O), and nitric acid (HNO_3).

To address this concern, we conducted two groups of ensemble experiments using the CESM1.2.2 model with interactive stratospheric chemistry.

We generated two 40-member ensembles: WQBO run and EQBO run. We first compute the composite mean meteorological fields during the WQBO and EQBO phases using MERRA2 reanalysis data. Stratospheric zonal wind, meridional wind, and temperature between 22°S–22°N and 84–4 hPa (Hansen et al., 2013) are nudged to these composite mean fields. Initial conditions for the 40 ensemble members were obtained from a 40-year free-running simulation of the CESM FW component, using outputs from December 1 of each year. Both ensemble experiments were integrated from December 1 to March 31. Importantly, both ensembles used the same sea surface temperatures, solar flux, and volcanic aerosol forcing, thereby minimizing the influences of ENSO, solar variability, and volcanic eruptions.

Figure R1 shows the difference in PSC area between the two ensemble runs. The PSC area during the WQBO phase is significantly larger than that during the EQBO phase, with the largest difference occurring near the 500 K isentropic level, consistent with both CALIPSO observations and SLIMCAT simulations (see Figure 2 in the manuscript). While the SLIMCAT results show a large PSC anomaly starting in December, CESM shows the anomaly emerging in January, likely because nudging began on December 1 and the polar vortex requires time to respond to QBO forcing. We analyzed the differences in temperature between the WQBO run and EQBO run. As shown in Figure R2, CESM reproduces the cold anomaly during WQBO, although the magnitude is smaller than that in ERA5. This temperature underestimation likely explains the weaker PSC area response (Figure R1 and Figure 2c in the manuscript).

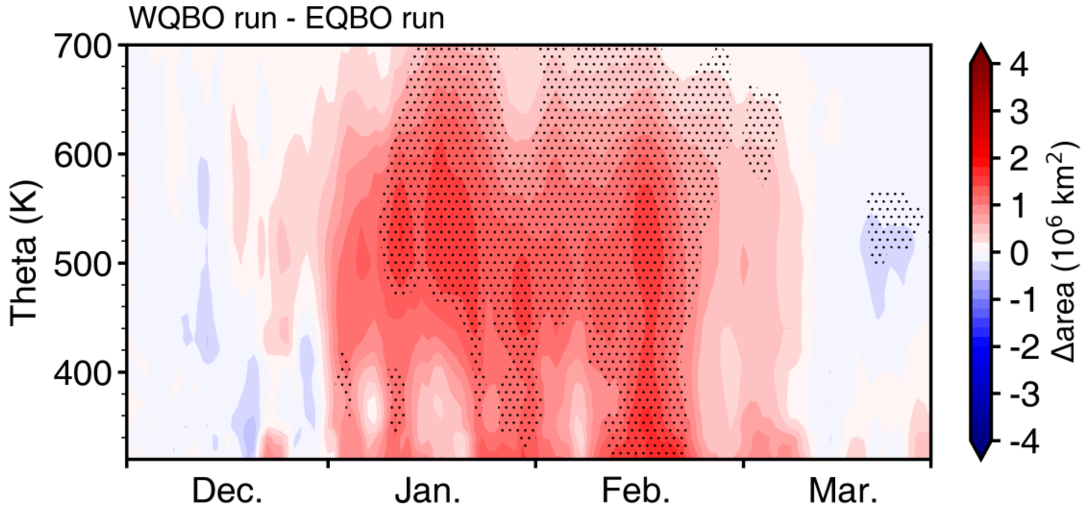

Figure R1. Differences in PSC coverage area between the WQBO run and the EQBO run. Black dotted regions indicate the differences in PSC area are statistically significant at the 95% confidence level according to the Student's *t*-test.

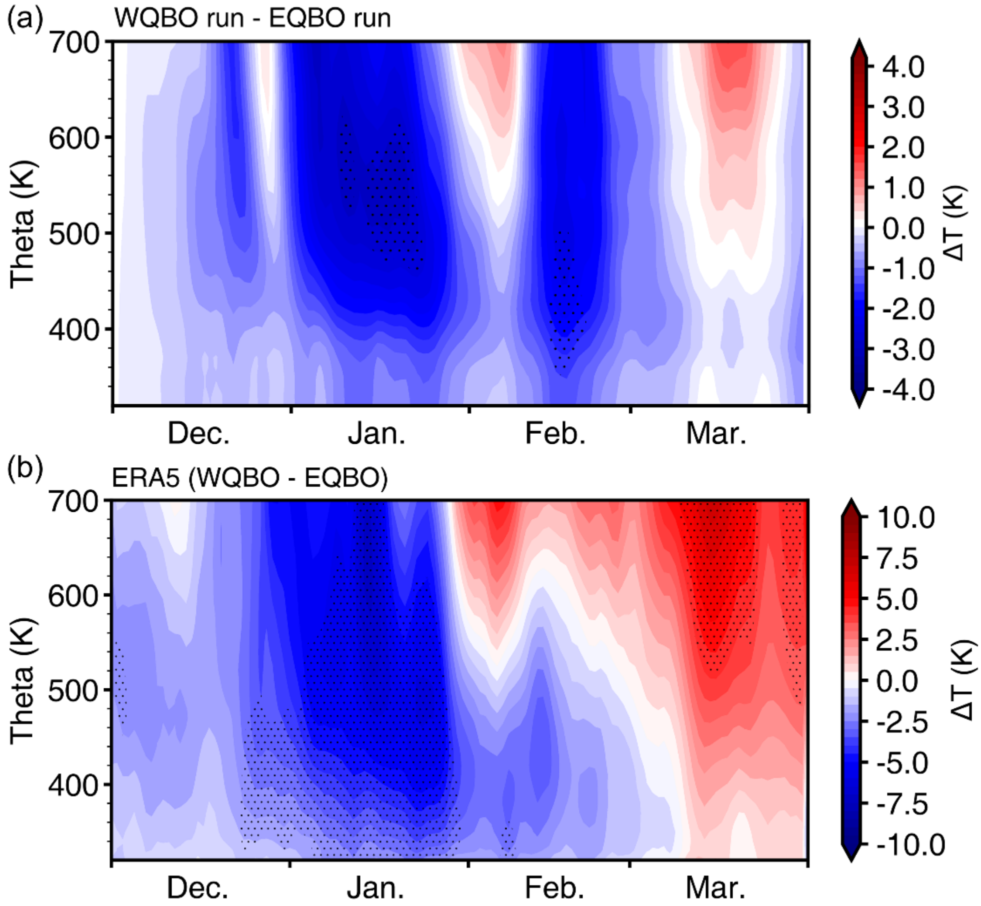

Figure R2. Time evolution of polar temperature differences between the WQBO and EQBO phases from (a) CESM and (b) ERA5. Black dotted regions indicate the differences in temperature are statistically significant at the 95% confidence level according to the Student's *t*-test.

We further compare the differences in H_2O and HNO_3 from CESM simulation (Figure R3), MLS observations (Figure R4), and SLIMCAT simulations (Figure R5) between the WQBO and EQBO phases. Both MLS and SLIMCAT show a positive H_2O anomaly between the 500–700 K isentropic levels from December to March. In contrast, the positive H_2O anomaly in CESM persists only through January. For HNO_3, both MLS and SLIMCAT show a negative anomaly between 400 and 500 K during WQBO, which is caused by the denitrification process. However, the CESM shows positive anomaly in HNO_3. This is likely due to the incomplete representation of denitrification and dehydration processes in CESM.

In addition to the simplified representation of denitrification and dehydration, we acknowledge that internal feedback mechanisms in CESM may also contribute to the HNO_3 anomalies. Further investigation would be needed to disentangle these effects.

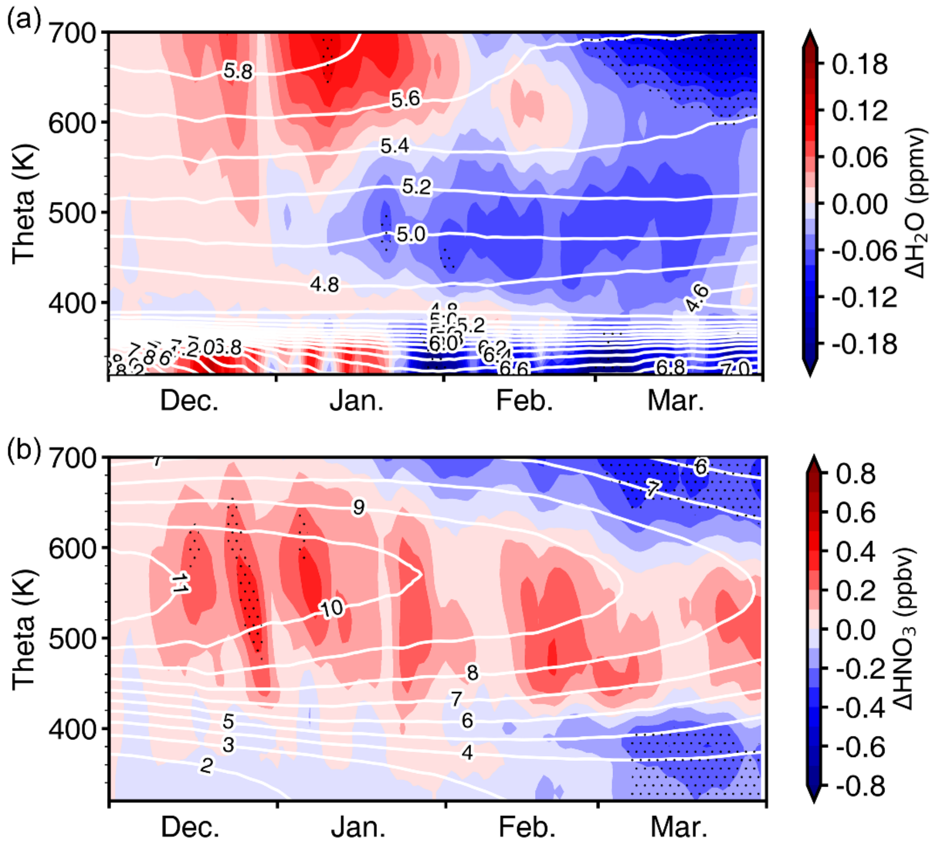

Figure R3. Differences in (a) H_2O and (b) HNO_3 between the WQBO run and EQBO run from CESM. The white contours are their climatological concentration. Black dotted regions indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

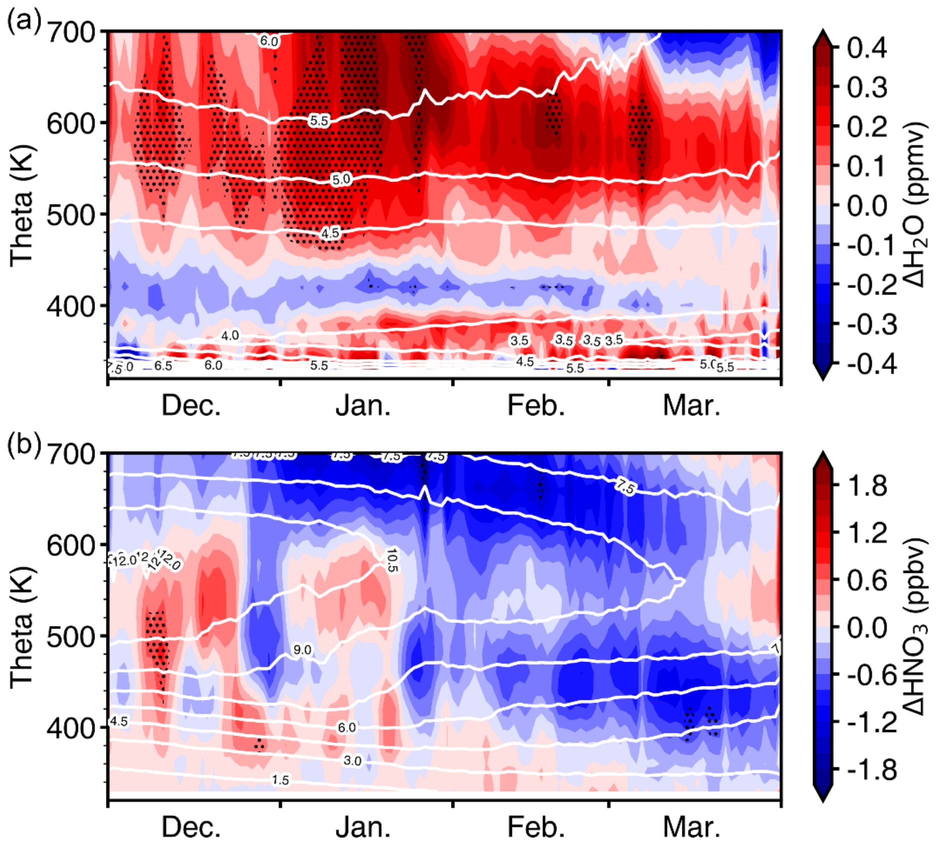

Figure R4. Differences in (a) H_2O and (b) HNO_3 between the WQBO and EQBO phases from MLS observations. The white contours are their climatological concentration. Black dotted regions indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

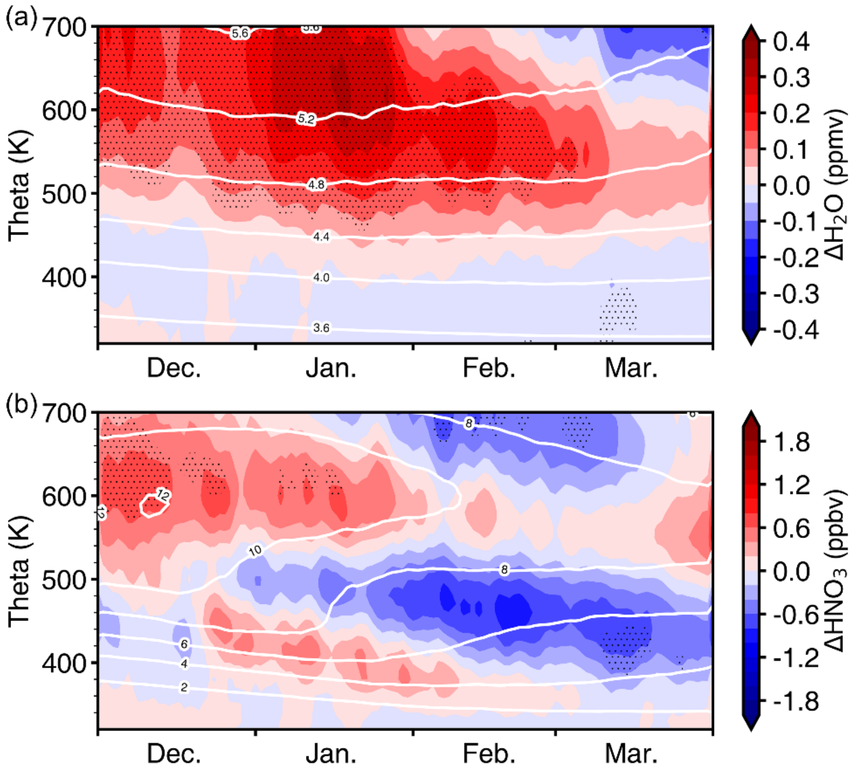

Figure R5. Differences in (a) H_2O and (b) HNO_3 between the WQBO and EQBO phases from SLIMCAT observations. The white contours are their climatological concentration. Black dotted regions indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

These comparisons reveal that while CESM can qualitatively reproduce the temperature response to QBO, it underestimates the impact on PSCs and fails to capture the observed H_2O and HNO_3 responses. Therefore, using CESM for further sensitivity experiments would introduce greater uncertainties. For this reason, we did not conduct further sensitivity experiments using the CESM. We acknowledge that the composite differences derived from reanalysis and SLIMCAT simulations may still include influences from other processes. We have added a clear statement of this limitation and its implications for interpretation in the revised manuscript. We added this paragraph to the revised manuscript: (Please see P23 and L524-L530 in the revised manuscript)

"Although our study provides evidence for the influence of QBO phases on Arctic PSC occurrence and associated stratospheric chemical composition changes, several limitations must be acknowledged. First, the SLIMCAT model used in this study is an offline chemical transport model driven by reanalysis data. Despite prescribing fixed ODS as well as climatological SAD and solar flux in the simulations, it is impossible to fully isolate the QBO signal from other factors such as ENSO, solar variability, and volcanic aerosols. Although composite analyses help to reveal QBO-related effects, the resulting anomalies may still contain contributions from other climate factors, which may contaminate the impact of QBO on Arctic PSC occurrence."

References:

Hansen, F., Matthes, K., and Gray, L. J.: Sensitivity of stratospheric dynamics and chemistry to QBO nudging width in the chemistry–climate model WACCM, J. Geophys. Res.: Atmos., 118, 10,464-10,474, https://doi.org/10.1002/jgrd.50812, 2013.

2. ENSO is a major interannual variability of the NH polar vortex. The authors show that the significance of the PSC occurrence anomalies during W/E-QBO is substantially reduced after excluding strong ENSO years (Fig. 5). However, it remains unclear how much of the observed differences are independently attributable to the QBO versus ENSO. Would the results change after regressing out the ENSO variability? I recommend that the authors clarify the influence of ENSO years quantitatively.

Response: Thank you for your valuable suggestion. As recommended, we applied a linear regression approach to remove the influence of ENSO. Specifically, we regressed the PSC occurrence frequency against the ONI index and obtained the regression coefficient a and intercept b, which were then used to calculate the residuals:

$$PSC_{residual} = PSC - (a \times ONI + b)$$

Here, PSC represents the original occurrence frequency, and $PSC_{residual}$ denotes the PSC occurrence frequency without the ENSO signal.

Figure R6 shows the differences in PSC occurrence between the WQBO and EQBO phases after removing the ENSO signal. Compared to Figure 4 in the manuscript, the significant positive anomalies remain in the polar regions, and our key conclusion still holds.

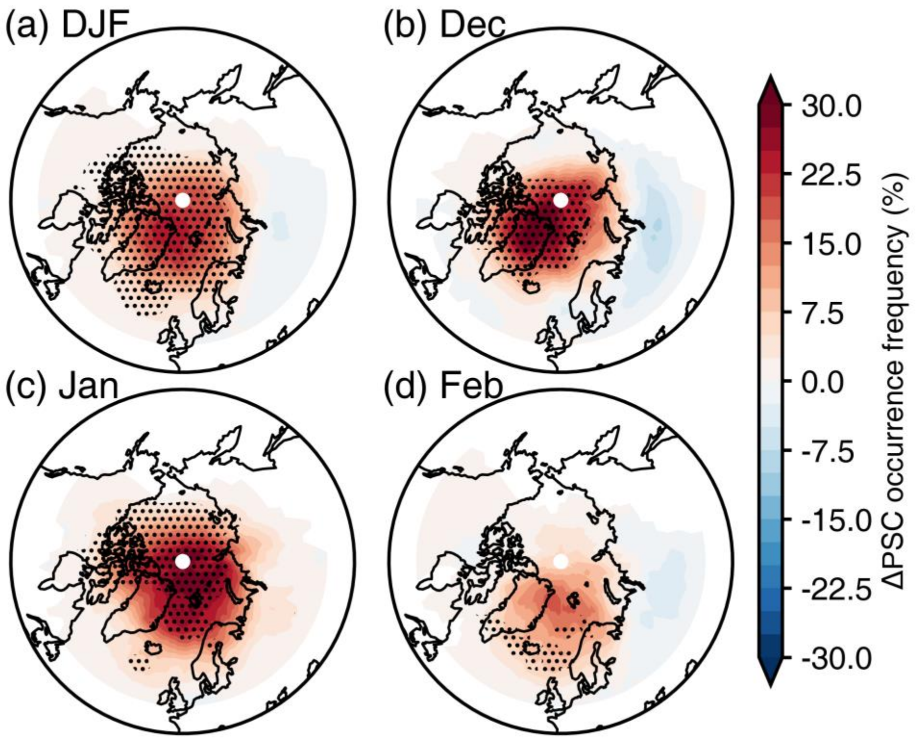

Figure R6. Differences in PSC occurrence frequency between the WQBO and EQBO phases after removing the ENSO signal on the 500 K isentropic level derived from the SLIMCAT simulations for the period 1979–2022 for (a) winter average (December to February), (b) December, (c) January, and (d) February. Black dotted regions indicate the differences in PSC occurrence frequency are statistically significant at the 95% confidence level according to the Student's *t*-test.

To further clarify the contribution of ENSO, Figure R7 presents the ENSO-

induced component ($a \times ONI + b$) in the composite difference. The results indicate that the ENSO-related PSC occurrence frequency anomalies are minimal and non-significant, with the differences between the WQBO and EQBO phases remaining within ±2%, suggesting a minor influence of ENSO.

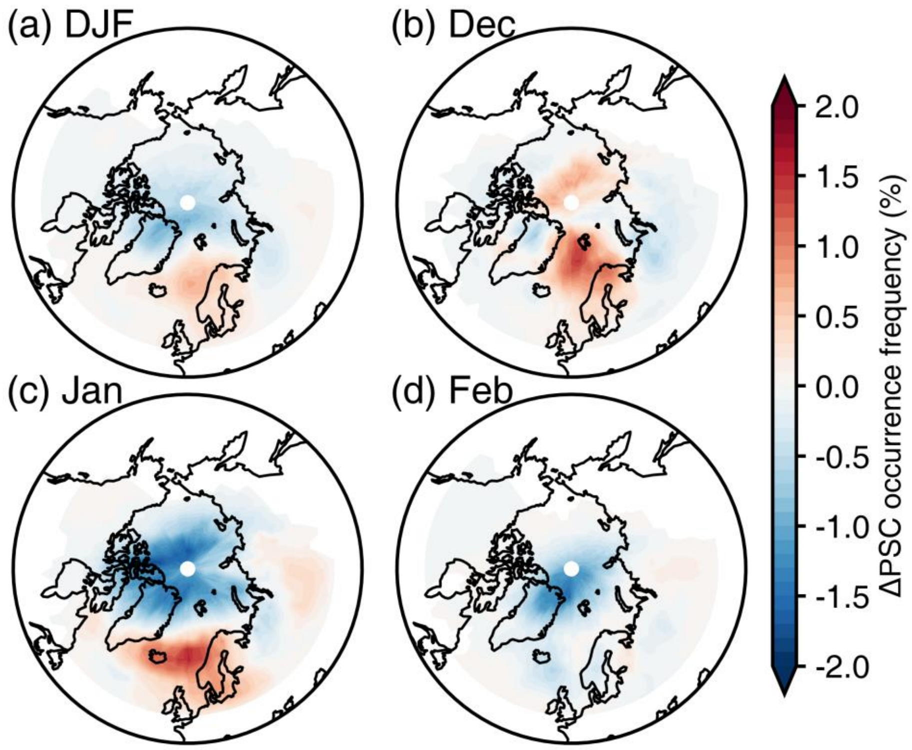

Figure R7. Differences in PSC occurrence frequency between the WQBO and EQBO phases induced by the ENSO signal on the 500 K isentropic level derived from the SLIMCAT simulations for the period 1979–2022 for (a) winter average (December to February), (b) December, (c) January, and (d) February. Black dotted regions indicate the differences in PSC occurrence frequency are statistically significant at the 95% confidence level according to the Student's *t*-test.

To verify the robustness of our method, we also applied the same regression approach to remove the QBO signal (by regressing PSC occurrence frequency against the QBO index). The differences in PSC occurrence after removing the QBO signal are shown in Figure R8. The results clearly show a substantial reduction in the magnitude of significant anomalies, confirming the effectiveness and reasonableness of our regression-based method for isolating ENSO influences.

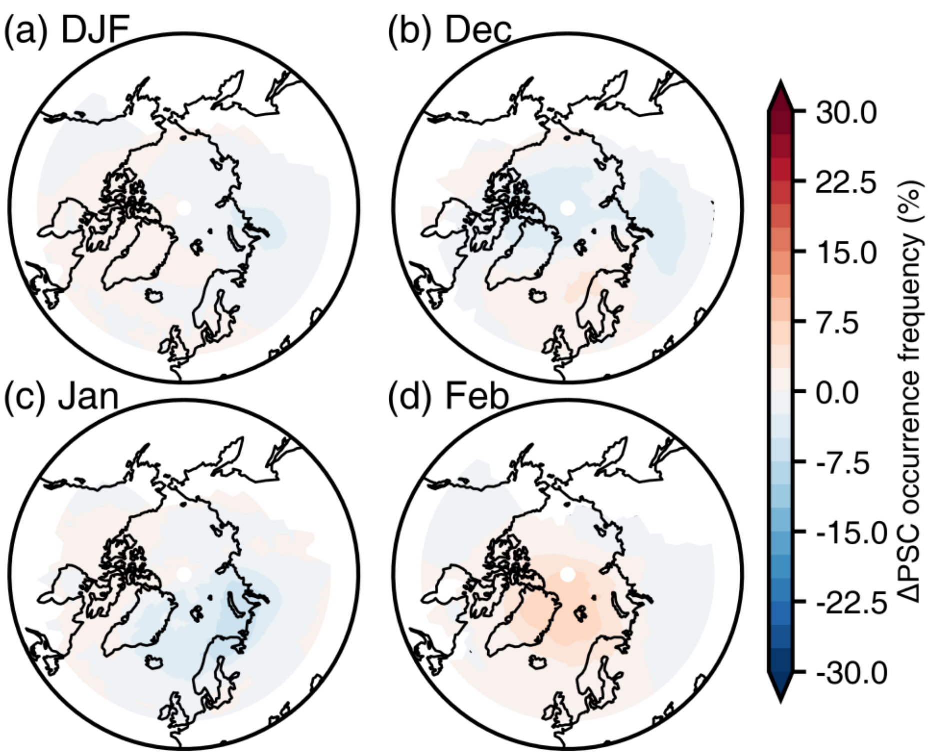

Figure R8. Differences in PSC occurrence frequency between the WQBO and EQBO phases after removing the QBO signal on the 500 K isentropic level derived from the SLIMCAT simulations for the period 1979–2022 for (a) winter average (December to February), (b) December, (c) January, and (d) February. Black dotted regions indicate the differences in PSC occurrence frequency are statistically significant at the 95% confidence level according to the Student's *t*-test.

3. It is clear that the chemical transport model (CTM) used in this study does not include interactive radiative-dynamical feedbacks.

This is an important limitation, as feedbacks between radiation, temperature, and circulation could alter the stratospheric response to QBO forcing. I recommend the authors explicitly discuss how the absence of radiative-dynamical coupling may affect their results, particularly the sensitivity experiments and the interpretation of temperature-driven PSC variability.

Response: Thank you for your insightful comment. As you noted, SLIMCAT used in our study is an offline chemical transport model that does not incorporate the

chemical-radiative-dynamical coupling process. However, SLIMCAT is driven by ERA5 reanalysis data, which incorporate the effects of radiative-dynamical processes. Moreover, SLIMCAT is designed to simulate realistic stratospheric chemistry as accurately as possible. Therefore, the results of the composite analysis reflect the impact of the QBO on Arctic stratospheric temperature, H_2O and HNO_3, and the PSC anomalies that we obtained are also largely caused by the QBO.

In our sensitivity analyses, we only considered the direct impact of QBO-induced H_2O changes on Arctic PSCs area, without accounting for the indirect effect by radiative cooling. In reality, as an important trace gas, stratospheric H_2O has a non-negligible influence on stratospheric temperature. Considering only the direct effect of H_2O changes may underestimate the overall influence of H_2O on PSC area in the sensitivity analysis. We have added a discussion of this limitation and its impact on the results of the sensitivity analyses in the revised manuscript: (Please see P23 and L530-L538)

"Second, SLIMCAT does not include the chemical-radiative-dynamical coupling process. As an important trace gas in the stratosphere, H_2O not only affects chemical reactions but also contributes to the radiative cooling of the stratosphere (Bi et al., 2011). Forster and Shine (2002) showed that a 1 ppmv increase in stratospheric H_2O results in a 0.8 K decrease in the temperature of the tropical lower stratosphere, with a more pronounced cooling of 1.4 K at high latitudes. Similarly, Tian et al. (2009) found that a 2 ppmv increase in H_2O causes a temperature decrease of more than 4 K in the stratosphere at high latitudes. In particular, due to the high sensitivity of PSC formation to temperature, the indirect effects of H_2O on PSCs by influencing temperature may be comparable to its direct effects. In our sensitivity analyses, we only consider the direct effect of H_2O changes on PSCs, without accounting for the indirect impact of radiative cooling induced by H_2O anomalies. This omission may lead to an underestimation of the QBO's impact on the Arctic PSC area in Fig. 11e–

h.”

Technical corrections:

1. In Figures 3 and 4 (PSC occurrence anomalies), the color scales could be optimized to better show the large positive anomalies. Currently, they are all just dark red.

Response: Thank you for your comment. We have adjusted the color scales in Figures 3 and 4 to enhance the visibility of large positive anomalies, ensuring a clearer distinction across the full range of values. (Please see P11 L279 and P12 L299 in the revised manuscript)

2. Abstract, Line 13: change "no studies have deeply analyzed" to "few studies have thoroughly analyzed" for a better scientific tone.

Response: Thank you for your comment. We have revised the sentence to “few studies have thoroughly analyzed” to improve the scientific tone. (Please see P1 and L11-L12 in the revised manuscript)

3. Line 157: "shown accurately simulate" missing "to".

Response: Thank you for your comment. We have added “to”. (Please see P6 and L162 in the revised manuscript)

4. Line 205: Repeating "samples"

Response: Thank you for your comment. The sentences are rephrased in the revised paper: (Please see P8 and L220-L221 in the revised manuscript)

“For example, of the 14 SLIMCAT simulations, 5 show values below 10 million km^3. In contrast, during the WQBO phase, all SLIMCAT simulations exceed 10 million km^3.”

5. Line 240: "variation overtime on the left panel". Typo: should be "over time"

Response: Thank you for your comment. Corrected. (Please see P10 and L261 in

the revised manuscript)

6. Line 409: "as strength of the polar vortex increases" --> "as the strength of the polar vortex increases"

Response: Thank you for your comment. Corrected. (Please see P19 and L433 in the revised manuscript)

7. Line 320: "Figure. 7" --> "Figure 7".

Response: Thank you for your comment. Corrected. (Please see P15 and L342 in the revised manuscript)