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]

August 2025

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 #3

Peer review

The manuscript investigates the influence of the quasi-biennial oscillation (QBO) on the occurrence of Arctic polar stratospheric clouds (PSCs) using CALIPSO satellite observations (2006-2021) and SLIMCAT model simulations (1979-2022). The study shows that PSC coverage is significantly larger during the westerly QBO (WQBO) phase compared to the easterly QBO (EQBO) phase, with a zonally asymmetric anomaly pattern. The authors analyze the mechanisms driving these differences, attributing them primarily to QBO-induced temperature changes, with secondary contributions from water vapor and nitric acid variations. Sensitivity tests further emphasize the dominant role of temperature.

The topic is highly relevant for understanding polar stratospheric chemistry and ozone depletion processes under future climate scenarios. The combined use of long-term satellite observations and chemical transport modeling is a strong methodological approach. The manuscript is generally well-structured, clearly written, and supported by comprehensive references. The sensitivity analysis provides valuable insight into the relative contributions of temperature, H2O, and HNO3.

I really enjoyed reading this work, and I believe it definitely deserves to be published. The manuscript is scientifically sound, well-presented, and makes a valuable contribution to the understanding of stratospheric processes. However, he authors might consider expanding it along the lines of the suggestions listed below.

General comments:

The CALIPSO dataset (16 years) is relatively short for robust statistical analysis, as noted by the authors. While SLIMCAT compensates with a longer timeframe, the observational validation remains limited. The authors may discuss potential biases or uncertainties arising from the short observational record and how SLIMCAT's longer simulations mitigate this. Moreover, statistically significant differences related to the QBO phase appear over regions hosting important ground-based lidar stations with long-term data records. Have the authors tried to verify their findings by also making use of these datasets and/or referring to published results?

Response: We appreciate the reviewer's insightful comment. The CALIPSO PSC dataset spans only 15 Arctic winters, which limits the robustness of the composite analyses. The results may be influenced by extreme events in specific years. To address this limitation, our study utilized the SLIMCAT long-term simulation (1979–2022) to supplement the relatively short observational record. These simulations help reduce the influence of individual outlier events on the composite analysis and enhance the statistical significance of the results. We have added a clarification of this issue in the revised manuscript. (Please see P4 L103-L109 and P22 L480-L488)

"From 2006 to 2021, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission continuously observed PSCs over both the Arctic and Antarctic, providing an unprecedented view of PSC occurrence and composition (Tritscher et al., 2021). In this study, we utilize CALIPSO PSC observations (Pitts et al., 2018) to investigate the potential impact of the QBO on Arctic PSC occurrence. However, the CALIPSO record includes only 15 Arctic winters, which may limit the statistical robustness of the results—for instance, the results could be affected by extreme events. To address this limitation, we also incorporate simulations from the SLIMCAT 3D chemical transport model, which spans over 40 years from 1979 to 2022, to complement the observational analysis."

"It is important to note that when the sample size is small, composite analysis results may be influenced by individual extreme events. For example, the negative anomaly in the PSC area derived from CALIPSO in December may have been driven by a few specific years, which is contrary to the theoretical expectations. To address this issue,

we used SLIMCAT simulations for the period 1979–2022 to reduce the impact of individual extreme events on the composite results. The results show that with the extension of the simulation period, a positive anomaly consistent with theoretical expectations occurs in December, and the statistical significance of the composite analysis is improved."

Furthermore, we acknowledge the value of long-term ground-based lidar records at key Arctic locations. As noted by Tesche et al. (2021), among Arctic sites suitable for PSC observations and with published PSC data, only Eureka and Ny-Ålesund have reported long-term lidar-based PSC measurements. However, we were unable to obtain the datasets from these sites. For instance, while Tritscher et al. (2021) included Ny-Ålesund lidar observations spanning 1995–2018 (see their Fig. 25), the underlying data were not accessible to us. We also contacted researchers at the Alfred Wegener Institute to request the Ny-Ålesund dataset, but unfortunately, we did not obtain the data.

Given these limitations, we try to verify our findings through comparison with published results and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) observations. To complement our CALIPSO-based analysis, we apply the "P18 method" to MIPAS data. We then perform composite analyses of the PSC area between the WQBO and EQBO phases. As shown in Figure R1, the results indicate a larger PSC area during the WQBO phase compared to the EQBO phase. We note that there are fewer points that pass the significance test, which may be due to limited sample size (5 samples for the WQBO and 3 samples for the EQBO). For this reason, we do not include the MIPAS composite results in the main manuscript. We only used the MIPAS data to validate the robustness of the CALIPSO and SLIMCAT PSC data, thereby enhancing the credibility of our results.

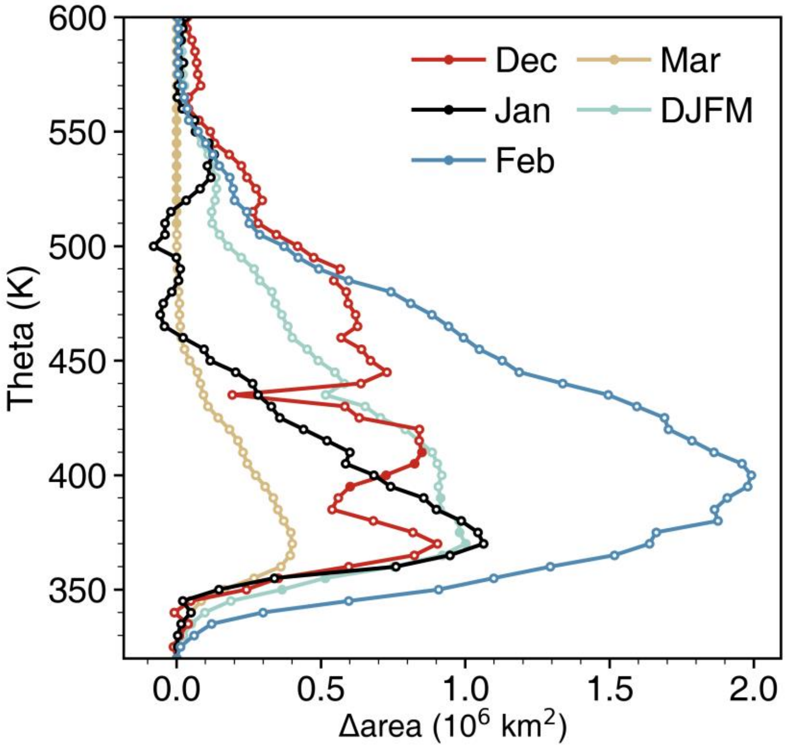

Figure R1. Differences in Arctic PSC area between the WQBO and EQBO phases derived from MIPAS during December–March (DJFM) and the DJFM average. Solid filled symbols indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

To further support our conclusions, we calculated the PSC volume by vertically integrating the PSC coverage area from CALIPSO, MIPAS, and SLIMCAT. Figure R2 presents the time series of PSC volume from CALIPSO and MIPAS satellite observations, alongside SLIMCAT simulations. Due to the higher detection threshold, CALIPSO's PSC volume is systematically lower than that of MIPAS and SLIMCAT. Nevertheless, the interannual variability in PSC volume is remarkably consistent across all three datasets. Moreover, the interannual variation in SLIMCAT PSC volume is generally consistent with the interannual variation in the PSC sighting frequencies at Ny-Ålesund as reported in Tritscher et al. (2021, Fig. 25). Inconsistent changes in some years may be due to the Ny-Ålesund site data can only represent PSC changes at the site location and do not

represent PSC changes in the entire Arctic region.

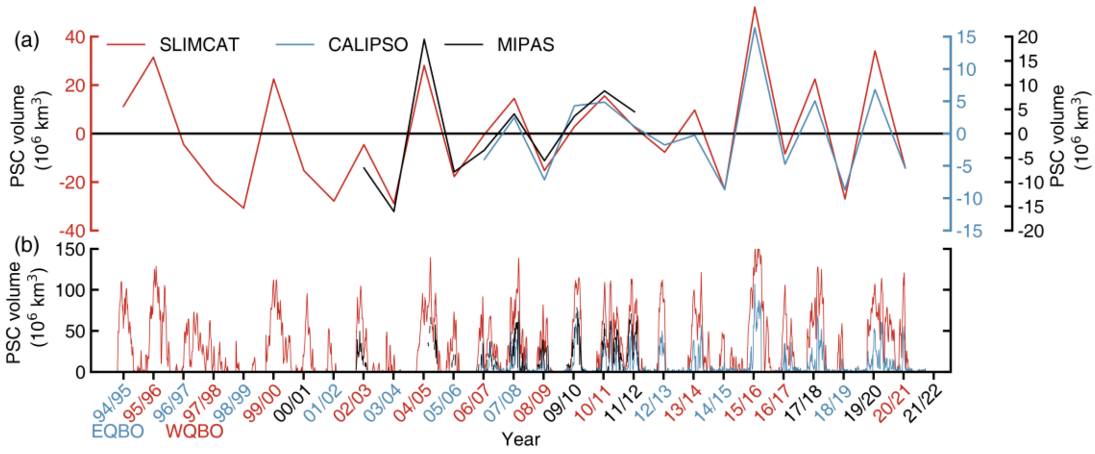

Figure R2. (a) Interannual variation of Arctic PSC volume (December–March mean) anomalies and (b) daily evolution of Arctic PSC volume observed by CALIPSO, MIPAS, and simulated by SLIMCAT. In the horizontal axis, blue and red labels indicate EQBO and WQBO winters, respectively. In panel (a), the different colours on the vertical axis represent different data sources.

References:

Tesche, M., Achtert, P., and Pitts, M. C.: On the best locations for ground-based polar stratospheric cloud (PSC) observations, Atmos. Chem. Phys., 21, 505–516, https://doi.org/10.5194/acp-21-505-2021, 2021.

Tritscher, I., Pitts, M. C., Poole, L. R., Alexander, S. P., Cairo, F., Chipperfield, M. P., Grooß, J., Höpfner, M., Lambert, A., Luo, B., Molleker, S., Orr, A., Salawitch, R., Snels, M., Spang, R., Woiwode, W., and Peter, T.: Polar Stratospheric Clouds: Satellite Observations, Processes, and Role in Ozone Depletion, Rev. Geophys., 59, https://doi.org/10.1029/2020RG000702, 2021.

The SLIMCAT model uses simplified PSC schemes (e.g., fixed number densities for NAT/ice particles). How might this affect the representation of denitrification/dehydration processes? The authors may speculate on how more sophisticated microphysics (e.g., size-resolved NAT sedimentation) would alter the conclusions.

Response: Thank you for your insightful comment regarding the simplified PSC scheme in SLIMCAT. We have added a discussion in the revised manuscript acknowledging the potential limitations of using prescribed particle radius or number densities for NAT and ice particles. While this simplification may affect the representation of denitrification and dehydration, we argue that the key QBO–PSC relationships reported in our study remain robust, as they are primarily driven by temperature. Nevertheless, we agree that implementing a more sophisticated microphysical scheme (e.g., including NAT/ice particle growth and sedimentation) would be a valuable extension in future work. The following statement was added to the discussion: (Please see P23 and L538-L544 in the revised manuscript)

"Finally, in SLIMCAT, denitrification and dehydration are implemented by assuming fixed sedimentation velocities for NAT and ice particles based on prescribed particle radii or number densities. This simplified scheme still shows discrepancies in H_2O and HNO_3 compared to MLS observations. Incorporating more complex microphysical schemes, such as the DLAPSE, which incorporates the nucleation, growth, and settlement processes of PSC particles, could improve the simulation of the spatial distribution of H_2O and HNO_3. However, detailed microphysical schemes are too expensive for long-term simulations. Moreover, as PSC formation is primarily modulated by temperature, the relationship between QBO and PSCs established in this study remains robust."

The authors dismiss BD circulation as the driver of H_2O anomalies but do not fully explore alternative mechanisms. As instance, the may clarify whether the H_2O accumulation is purely due to vortex isolation or if other processes (e.g., local tropopause temperature and permeability changes) may contribute.

Response: Thank you for your comment. We have examined the QBO-related differences in MLS H_2O between EQBO and WQBO phases during December–March over the 300–1 hPa (Figure R3). Our study focuses on the region north of 60 °N and around 30 hPa, where we observe statistically significant positive H_2O anomalies. In the manuscript, we attribute this anomaly primarily to vortex isolation. You mentioned the possibility that local tropopause temperature and permeability changes could also contribute. In polar regions, the tropopause is typically located near 300–200 hPa. We do observe that QBO significantly affects H_2O concentrations near the tropopause. However, in the region between the tropopause and our study level (30 hPa), the response of H_2O to the QBO exhibits inconsistent signs, indicating that the vertical variation in the H_2O is not continuous. Therefore, it is unlikely that the H_2O anomalies observed at 30 hPa are primarily influenced by local changes near the tropopause. The following sentences were added in the revised paper: (Please see P16 and L387-L391 in the revised manuscript)

"Changes in tropopause temperature and permeability may also influence stratospheric H_2O. In the Arctic, the tropopause is typically located around the 320 K potential temperature level. However, we note that the positive H_2O anomalies observed and simulated in our study are mainly concentrated above the 450 K, with no significant positive H_2O anomaly signals detected on 320 K–450 K (Fig. 8a and c). Therefore, we consider that local processes at the tropopause are unlikely to be the primary drivers of the H_2O anomalies above the 450 K."

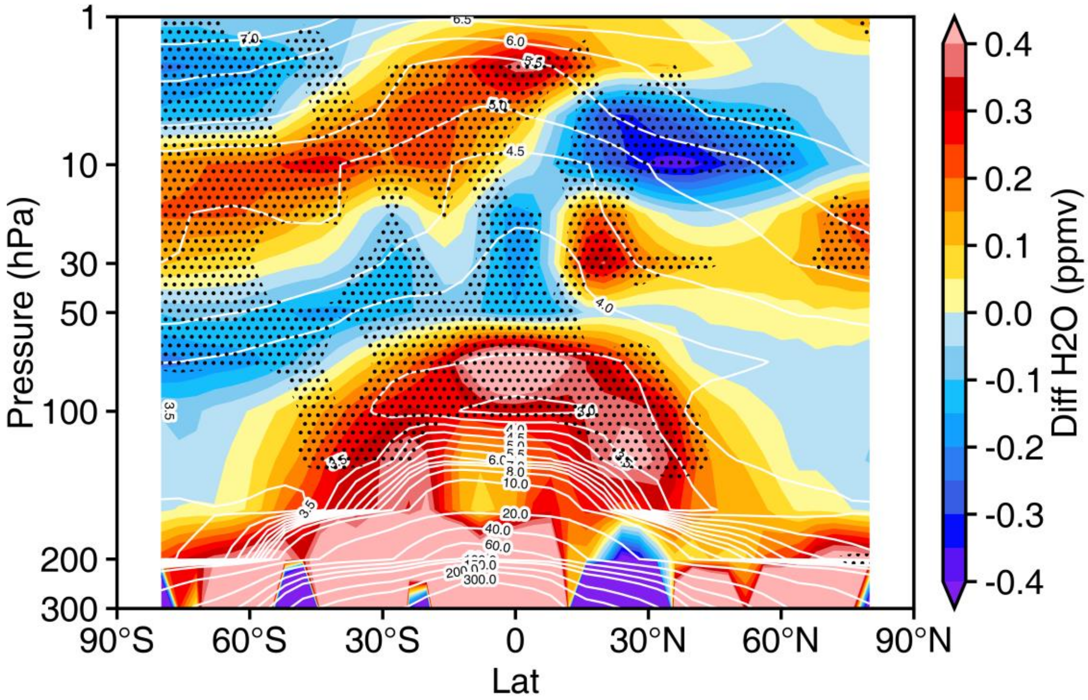

Figure R3. Climatological H_2O (white contours) and the differences in zonal H_2O between WQBO and EQBO phases (shadings, WQBO–EQBO) derived from MLS data for the period 2004−2021. Black dotted regions indicate the differences in H_2O are statistically significant at the 95% confidence level according to the Student's *t*-test.

In addition, we have considered two other potential contributions to the H_2O anomalies in the manuscript:

(1) Methane oxidation, which contributes to H_2O in the middle and upper stratosphere. However, its effect is weaker in the lower stratosphere, where methane oxidation rates are relatively low. (Please see P16 and L365-L372 in the revised manuscript)

(2) Dehydration by ice PSCs, which could remove H_2O from the stratosphere. However, because Arctic temperatures are generally not low enough to support the widespread formation of ice PSCs, this process plays a relatively minor role in the Arctic compared to the Antarctic. (Please see P19 and L441-L449 in the revised manuscript)

To further verify the relationship between H_2O and the polar vortex, we present a time series of zonal-mean H_2O and zonal-mean zonal wind at 30 hPa (Figure R4). SLIMCAT successfully reproduced the key characteristics of H_2O variations observed by MLS, including high-H_2O events in the Arctic in 2011, 2015, and 2020. In all three years, following a sharp weakening of the zonal-mean wind near 60°N (vortex breakdown), H_2O concentrations dropped rapidly, suggesting a strong link between water vapor and vortex.

Unlike in the Arctic, a H_2O minimum occurs every year after June in the Antarctic. This is due to the colder temperatures in Antarctica, where ice PSCs form every year, causing stratospheric dehydration. We also note that increases in zonal wind near 60°S are accompanied by decreased H_2O concentrations around 45°S in the southern hemisphere winter, consistent with our conclusion that a stronger polar vortex prevents the transport of high-moisture air at high latitudes to mid-latitudes, resulting in reduced midlatitude H_2O. The above results of the comparison indicate that polar vortex has a significant impact on H_2O near 30 hPa.

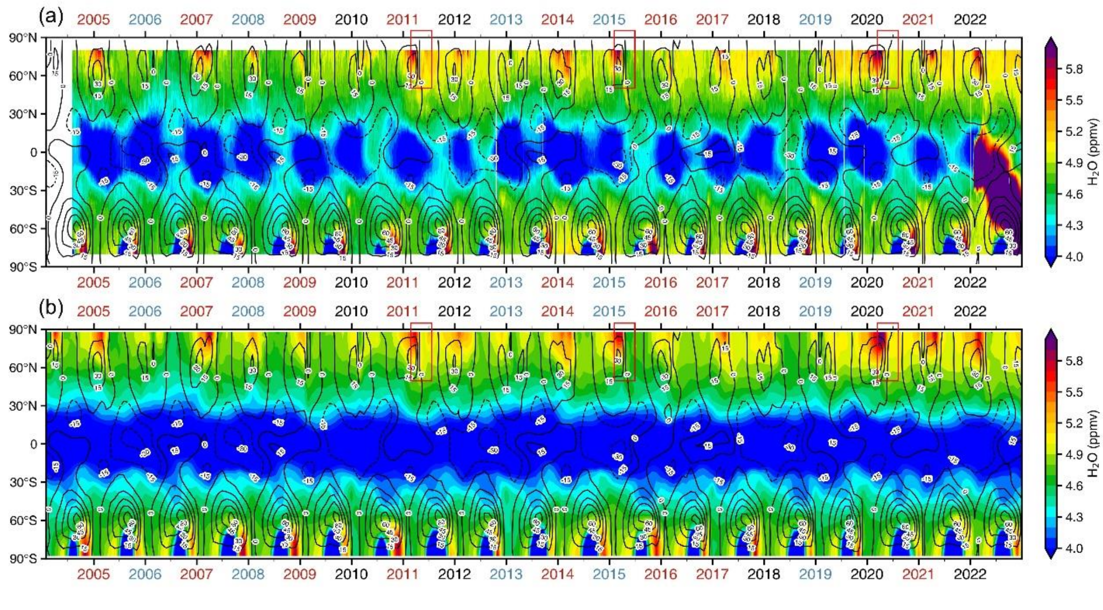

Figure R4. Temporal evolution of zonal-mean H_2O (shading) and zonal-mean zonal wind (contours) at 30 hPa from (a) MLS observations and (b) SLIMCAT simulations.

While the paper mentions that PSC changes may affect ozone, the connection is not quantified. How much could QBO-driven PSC variability contribute to interannual ozone loss differences? The author may add a speculative estimate based on some proxy, as the volume of PSCs below a certain temperature threshold and subsequent ozone loss during spring.

Response: Thank you for your suggestion. Previous studies have shown a strong correlation between Arctic column ozone loss and PSC volume, with a linear regression slope of 2.1 ± 0.2 DU per 10^6 km^3 and a correlation coefficient of 0.96 (Rex et al., 2004). We performed vertical integration of the PSC area from CALIPSO, MIPAS, and SLIMCAT to obtain their respective PSC volumes. As shown in Table 1, the PSC volumes during the WQBO and EQBO phases and their differences are summarized. Based on the regression relationship from Rex et al. (2004), the QBO could potentially lead to an interannual variation in springtime ozone loss of approximately 8.7 DU (CALIPSO) to 46.6 DU (SLIMCAT). Here, we did not independently calculate the relationship between PSC volume and ozone loss. This is because, although PSC volume and ozone loss rate exhibit a strong linear relationship, this relationship includes not only the chemical contribution of PSCs but also the dynamical contribution. In other words, the QBO-induced interannual variation in spring ozone loss mentioned above is not solely caused by PSC changes. Therefore, a dedicated method is needed to quantify the chemical impact of PSCs on ozone depletion.

Table 1. PSC volumes for CALIPSO, MIPAS, and SLIMCAT during WQBO and EQBO phases and differences between the WQBO and EQBO phases (in 10^6 km^3).

	CALIPSO	MIPAS	SLIMCAT
WQBO	10.82	19.13	42.29
EQBO	6.68	10.05	20.08
Diff	4.14	9.08	22.21

Here, we calculate the chemical ozone loss by using the "passive odd-oxygen" tracer in SLIMCAT (Feng et al., 2005). The passive tracer is set equal to O_x = $O(^3P)$ + $O(^1D)$ + O_3 (involving both chemical and dynamical processes) on the first day of the month, and it is advected passively without any chemical process. The difference between this passive odd-oxygen (OXP) and chemically integrated O_x represents the chemical ozone loss (O_3 − OXP, hereafter referred to as Chem O_3) (Wang et al., 2021).

Figure R5 and Figure R6 show the differences in O_3 and Chem O_3, respectively, between the WQBO and EQBO phases. We note that during the WQBO phase, in December and January (Figure R5a and b), there are negative O_3 anomalies over the Arctic on the 500–700 K isentropic levels. However, the center of this negative anomaly does not agree well with the center of the PSC area positive anomaly shown in Fig. 2 in the manuscript, suggesting that the ozone anomaly in this region is not mainly driven by chemical processes. Furthermore, in December and January (Figure R6 a and b), Chem O_3 exhibits positive anomalies over the Arctic on the 500–700 K isentropic levels, indicating that the observed O_3 decrease in this region is not due to chemical loss, but rather to dynamical processes. Starting in January, significant chemical ozone loss emerges over the Arctic, with a peak anomaly of approximately 0.05 ppmv, spatially coinciding with the PSC area positive anomaly region.

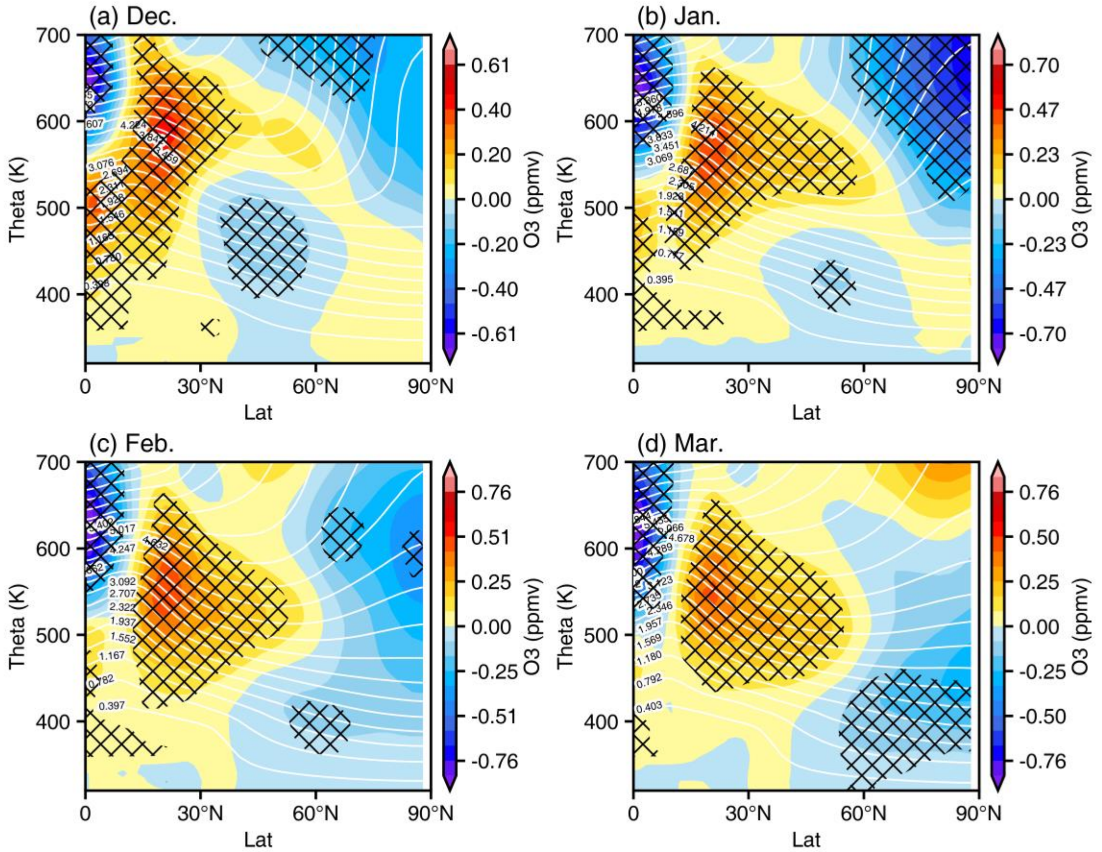

Figure R5. Climatological O_3 (white contours) and the differences in zonal-mean O_3 between WQBO and EQBO phases (shadings, WQBO–EQBO) derived from SLIMCAT for the period 1979-2022. Black shading regions indicate the differences in O_3 are statistically significant at the 95% confidence level according to the Student's *t*-test.

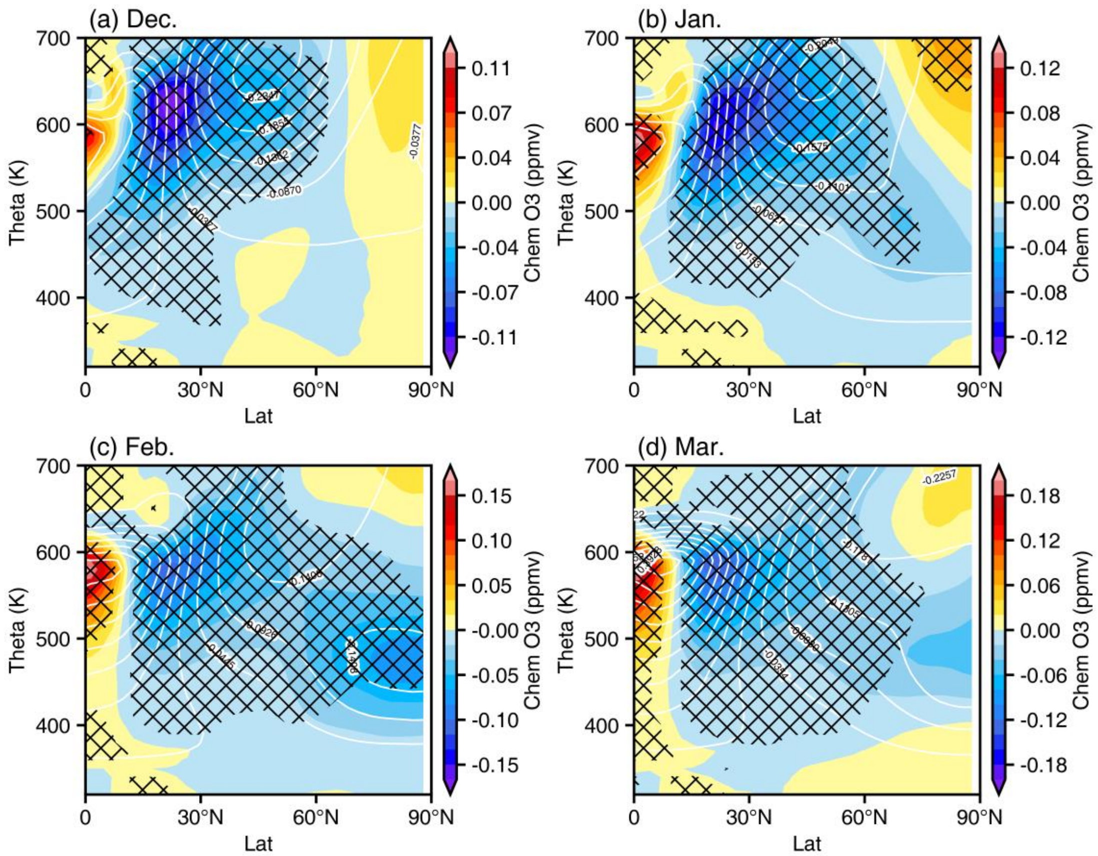

Figure R6. Climatological Chem O_3 (white contours) and the differences in zonal-mean Chem O_3 between WQBO and EQBO phases (shadings, WQBO–EQBO) derived from SLIMCAT for the period 1979-2022. Black shading regions indicate the differences in Chem O_3 are statistically significant at the 95% confidence level according to the Student's *t*-test.

Figure R7 presents the vertical profiles of O_3 and Chem O_3 anomalies over the Arctic from December to March between the WQBO and EQBO phases. The chemical ozone depletion associated with PSC anomalies primarily occurs near 500 K isentropic level, which peaks in February, and is nearly zero in December. This seasonal pattern is related to solar radiation: during December, the Arctic experiences polar night, and the absence of ultraviolet radiation inhibits ozone depletion reactions. In February, the chemical ozone depletion reaches approximately 0.06 ppmv at around 480 K, while the O_3 anomaly at the same level is about 0.12 ppmv, indicating that chemical processes account for roughly 50%

of the total ozone loss. Although the absolute monthly chemical depletion is relatively small, its cumulative effect can result in a large impact on springtime ozone.

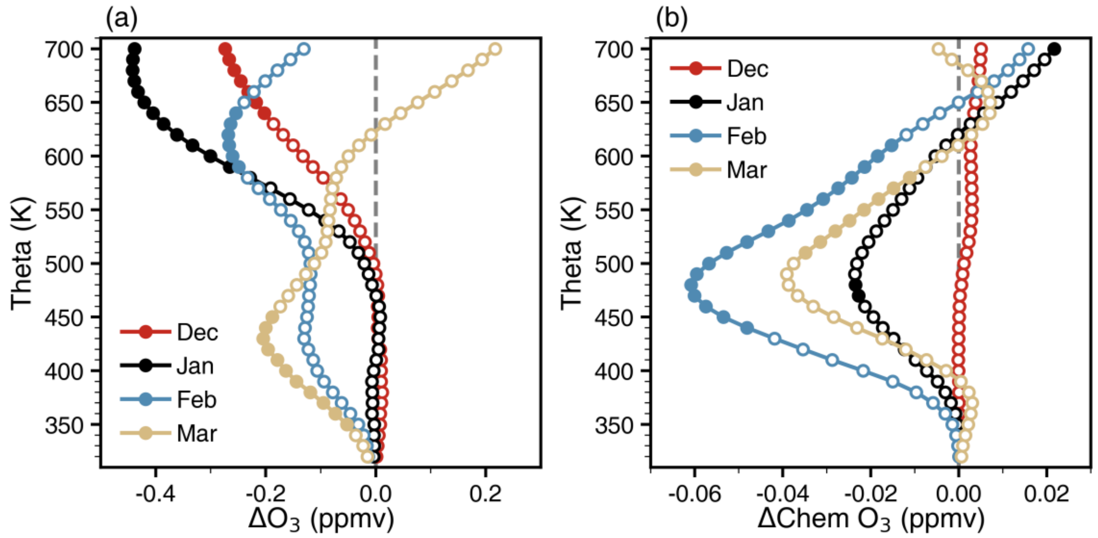

Figure R7. Vertical profiles of the differences in (a) O_3 and (b) Chem O_3 over the Arctic between WQBO and EQBO phases from December to March. Solid filled symbols indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

References:

Rex, M., Salawitch, R. J., von der Gathen, P., Harris, N. R. P., Chipperfield, M. P., and Naujokat, B.: Arctic ozone loss and climate change, Geophys. Res. Lett., 31, L04116, https://doi.org/10.1029/2003GL018844, 2004.

Feng, W., Chipperfield, M. P., Roscoe, H. K., Remedios, J. J., Waterfall, A. M., Stiller, G. P., Glatthor, N., Höpfner, M., and Wang, D.-Y.: Three-dimensional model study of the Antarctic ozone hole in 2002 and comparison with 2000, Journal of the atmospheric sciences, 62, 822–837, https://doi.org/10.1175/JAS-3335.1, 2005.

Wang, Z., Zhang, J., Wang, T., Feng, W., Hu, Y., and Xu, X.: Analysis of the Antarctic Ozone Hole in November, Journal of Climate, 1–53,

https://doi.org/10.1175/JCLI-D-20-0906.1, 2021.

The conclusion notes QBO disruptions under climate change but does not explore how projected QBO changes (e.g., weaker amplitude) might alter PSC trends, this may be briefly discuss this in the "Discussion and Conclusions" section.

Response: Thank you for the insightful suggestion. In response, we have added a brief discussion to highlight how projected QBO changes may alter PSC trends. We note that a weakened QBO amplitude in the lower stratosphere may reduce its influence on Arctic temperatures, thereby reducing its effect on PSC formation. The following sentences were added in the revised paper: (Please see P24 and L548-L549 in the revised manuscript)

"A future weakening of the QBO amplitude (Diallo et al., 2022) may reduce its modulation of the polar vortex and temperature in the Arctic stratosphere, thereby reducing its effect on PSC variability."

Specific comments:

- Figure 1: It could be beneficial to add to the data points a colour coding the ENSO phase, to visually show what is the possible impact on PSC area. Moreover, it would help to quantify the slopes and R2 values of the regression lines for CALIPSO and SLIMCAT.

Response: Thank you for the helpful suggestion. In the revised Figure 1, we have added color coding to the data points based on the ENSO phase (El Niño and La Niña,), allowing for a visual assessment of ENSO's potential influence on the PSC area. Additionally, we now include the slope and R^2 of the regression lines for both CALIPSO and SLIMCAT, to provide a clearer quantitative comparison of the relationships. (Please see P8 and L228-L239 in the revised manuscript)

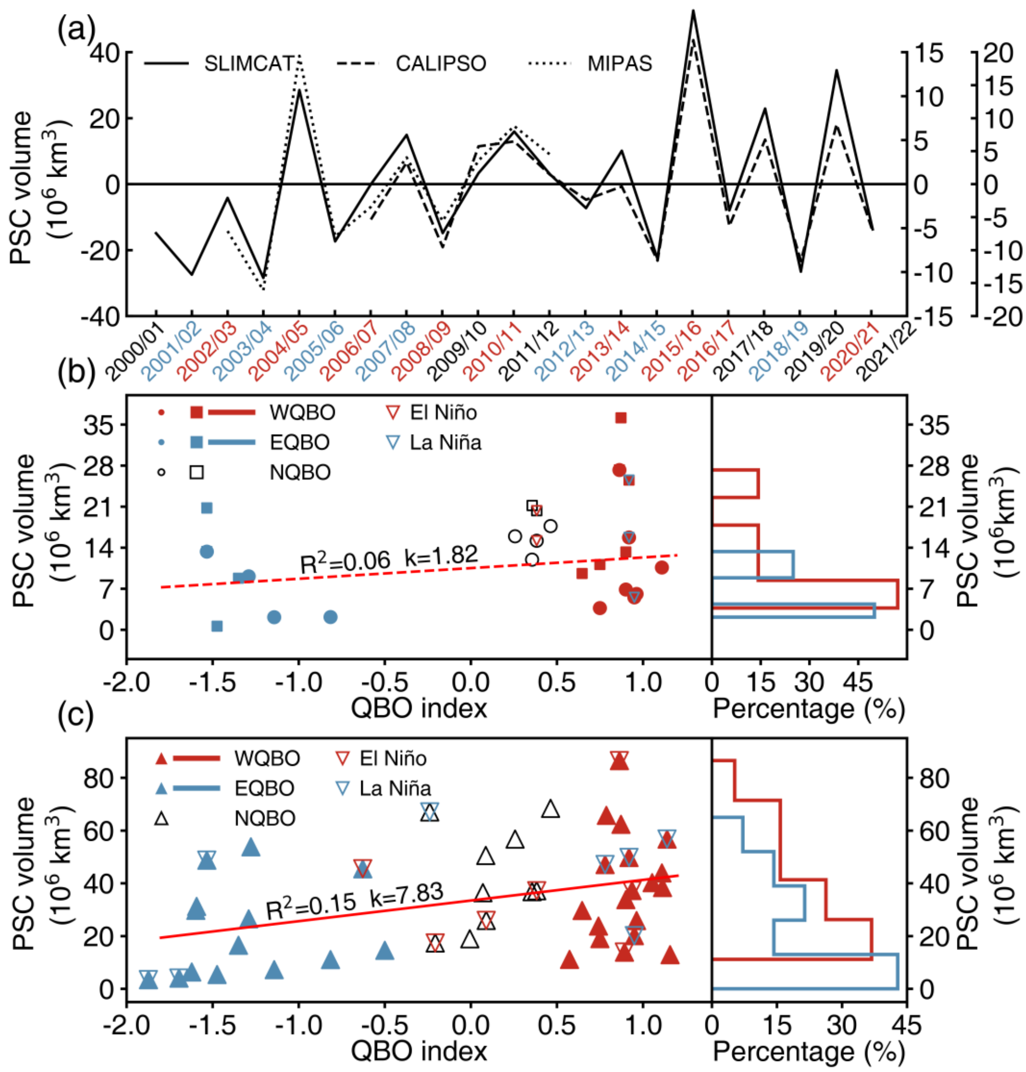

Figure 1. (a) Interannual variation of Arctic PSC volume (December–March mean) anomalies observed by CALIPSO and MIPAS and simulated by SLIMCAT. In the horizontal axis, blue and red labels indicate EQBO and WQBO winters, respectively. (b, c) Arctic PSC volume (December–March mean) plotted against the QBO index in December (left) from (b) CALIPSO and MIPAS observations and (c) SLIMCAT simulations. Triangles represent the PSC volume simulated by SLIMCAT from 1980 to 2022, circles represent the PSC volume observed by CALIPSO from 2007 to 2021, and squares represent the PSC volume observed by MIPAS from 2003 to 2012. Blue markers and red markers represent the PSC volume during EQBO and WQBO, respectively. In addition, red and blue downward-pointing triangles denote El Niño and La Niña winters, respectively. The red lines show the linear regression of the

QBO index and the PSC volume for SLIMCAT and CALIPSO, respectively, with slopes (k) and coefficients of determination (R^2) labeled. The solid line is statistically significant at the 95% confidence level, while the dashed line is not. The probability distribution functions (PDF) of the PSC volume for the two QBO phases are shown on the right in (b) for CALIPSO and (c) for SLIMCAT.

- Table 2: The description of "W_less HNO_3" and "E_more HNO_3" could be clearer. Specify that adding HNO_3 during WQBO reduces PSCs (due to less denitrification).

Response: Thank you for your comment. We revised the descriptions in Table 2. (Please see P20 and L459-L462 in the revised manuscript)

Table 2. Description of the sensitivity analyses, where Δ represents the differences between the WQBO and EQBO phases.

Name	*Change*	*PSC area change*	*Description*
W_high T	*T-50 %×ΔT*[1]	*Decrease*[2]	*The temperature during the WQBO phase is subtracted by 50% of the temperature differences, which could raise the temperature and decrease the PSC area.*
E_low T	*T+50 %×ΔT*	*Increase*	*The temperature during the EQBO phase is added by 50% of the temperature differences, which could reduce the temperature and increase the PSC area.*
W_less H_2O	*H_2O-50 %×ΔH_2O*	*Decrease*	*The H_2O during the WQBO phase is subtracted by 50% of the H_2O differences, which could decrease the H_2O concentration and the PSC area.*
E_more H_2O	*H_2O+50 %×ΔH_2O*	*Increase*	*The H_2O during the EQBO phase is added by 50% of the H_2O differences, which could increase the H_2O concentration and the PSC area.*
W_less HNO_3	*HNO_3+50 %×ΔHNO_3*	*Decrease*	*The HNO_3 during the WQBO phase is added by 50% of the HNO_3 differences, which could decrease the HNO_3 concentration and the PSC area.*

E_more HNO_3	***HNO_3-50 %×ΔHNO_3***	***Increase***	***The HNO_3 during the EQBO phase is subtracted by 50% of the HNO_3 differences, which could increase the HNO_3 concentration and the PSC area.***

- Line 20-22: It would be beneficial to clarify early that H2O anomalies have a small direct but possibly significant indirect impact via radiative cooling. See Forster and Shine (2002) for quantitative estimates.

Response: Thank you for your valuable suggestion. We agree that stratospheric H_2O can indirectly affect PSCs through radiative cooling. However, this indirect effect is not analyzed in the current study, as it lies beyond the scope of this study. Nevertheless, we have acknowledged this limitation and discussed the potential impact of radiative cooling by H_2O on PSCs in the revised manuscript. The following sentences are added in the revised paper: (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."

- Section 2.2: A brief summary of previous validations of SLIMCAT for PSC representation would strengthen confidence. Relevant references may include Feng et al. (2021) and Li et al. (2024).

Response: Thank you for your comment. We have revised Section 2.2 to provide a more detailed summary of the evaluation conducted by Li et al. (2024), which compared SLIMCAT results with CALIPSO observations. We also reviewed Feng et al. (2021), but found that this study does not assess the PSC representation in SLIMCAT. Therefore, we have not cited it in this context. The following sentences are revised in the revised paper: (Please see P6-P7 and L188-L189)

"Li et al. (2024) showed that the PSC area derived from SLIMCAT is in good agreement with CALIPSO observations in terms of seasonal evolution, interannual variability, and spatial distribution. This strengthens confidence in the performance of the SLIMCAT model in simulating PSCs."

- Figure 4 vs. Figure 5: Please explicitly state that the ENSO exclusion does not alter the primary conclusions, but does reduce significance areas due to reduced sample size.

Response: Thank you for your comment. The following sentences are revised in the revised paper: (Please see P13 and L306-L308)

"The results show similar patterns to Fig. 4, indicating that strong ENSO exclusion maintains the primary conclusions despite reducing the spatial significance extent due to reduced sample size."

- Page 20 (Sensitivity analyses): Consider emphasizing that temperature effects dominate mainly because the Arctic stratospheric temperatures are often near PSC thresholds, making them highly sensitive (Pitts et al., 2018).

Response: Thank you for your comment. The following sentences are rephrased in the revised paper: (Please see P21 and L468-L469)

"Since Arctic temperatures are concentrated around the PSC formation threshold (Fig. 7), PSCs are highly sensitive to temperature changes, and even small changes in temperature would result in significant variations in PSC."

- Minor: Typos like "SLICMAT" instead of "SLIMCAT" (Page 4) should be corrected.

Response: Thank you for your comment. Corrected. (Please see P4 and L108 in the revised manuscript)