Response to Referee's Comments

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Title: The Impact of the Stratospher

ic Quasi-Biennial Oscillation on Arctic Polar Stratospheric

Cloud Occurrence

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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 #1

This manuscript investigates the impact of the stratospheric quasi-biennial oscillation (QBO) on the occurrence of Arctic polar stratospheric clouds (PSCs). This is an interesting topic, as PSCs play a critical role in ozone depletion. The QBO is a major mode of variability in the tropical stratosphere and its effects on the polar vortex and ozone have been studied, but its specific impact on PSCs has not been explored in depth. Therefore, this study fills a gap in the existing literature and is innovative. In this study, using the CALIPSO satellite observations and the SLIMCAT chemical transport model, the authors found that QBO can have a significant effect on the Arctic PSC, characterized by a clear zonal asymmetry. Moreover, the authors also found that QBO affects Arctic H_2O and HNO_3 in two different ways. These conclusions are based on observations and simulations and appear reasonable. Overall, this paper is well written. However, part of the analysis needs to be clarified and improved. I encourage the authors to revise it before publication.

General comments:

1. You mentioned that during the EQBO phase, the distribution of the PSC area is skewed, with a peak near zero. This is understandable, as the polar vortex is generally weaker and the temperatures inside the vortex are higher during the EQBO phase, which is unfavorable for PSC formation. However, during the WQBO phase, the polar vortex is stronger and the temperatures inside the vortex are lower, which favors PSC formation. So why is the distribution of the PSC area during the WQBO phase not a skewed distribution with a higher peak, but rather a uniform distribution?

Response: Thank you for your comment. As you mentioned, the polar vortex is generally stronger and colder during the WQBO phase, and weaker and warmer during the EQBO phase. Since the QBO influences Arctic PSCs primarily through its modulation of stratospheric temperature, PSC area is typically smaller during

EQBO and larger during WQBO, which is consistent with our findings.

To understand the distribution patterns, we examined the probability density functions (PDF) of Arctic stratospheric temperature and polar vortex strength (defined by the zonal-mean zonal wind at 500 K isentropic level) during the WQBO, EQBO, and neutral QBO (NQBO) phases (Figure R1). The results show that extremely low temperatures and strong vortex events are rare during all QBO phases, suggesting that the frequency of extreme PSC occurrences will be limited.

We further analyzed the PDF of PSC volume during the WQBO and EQBO phases (see Figure 1 in the manuscript), and find that both distributions exhibit a skewed pattern and the frequency of extreme PSC is very small, which is consistent with theoretical expectations. Although the shape of the distribution may differ depending on the metric used (area vs. volume), the key conclusion remains robust: PSC occurrence is more frequent and more extensive during the WQBO phase compared to the EQBO phase.

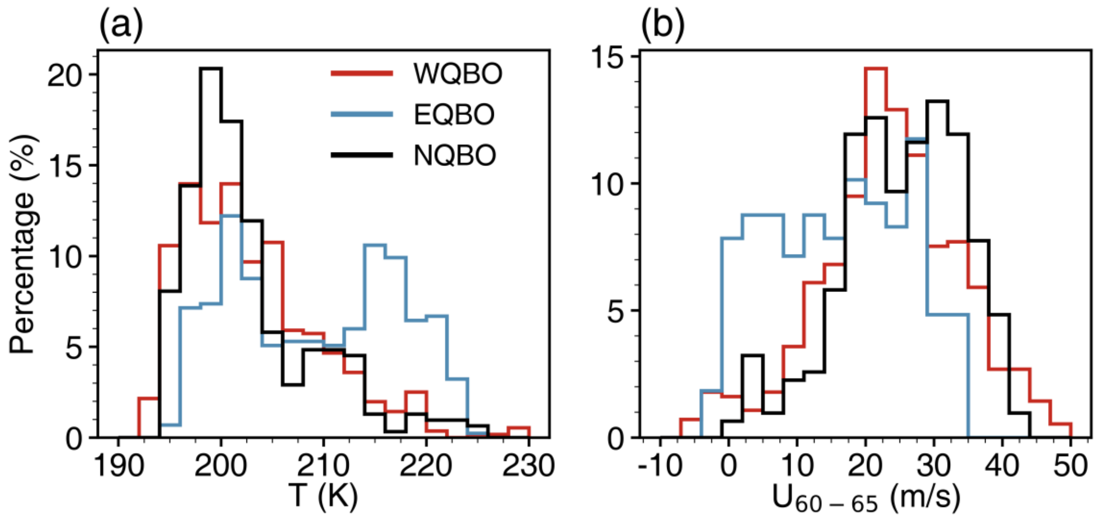

Figure R1. The probability distribution functions (PDF) of (a) temperature over the Arctic region (60°N–90°N) and (b) zonal-mean zonal wind between 60°N and 65°N during different QBO phases at 500 K isentropic level. Red lines represent the WQBO phase, blue lines represent the EQBO phase, and black lines represent the NQBO phase.

2. I suggest dividing Section 3 into several subsections to improve the structural clarity and logical coherence of the manuscript, such as (1) The impact of QBO on PSCs; and (2) The key factors responsible for QBO's impact.

Response: Thank you for your suggestion. We agree that dividing Section 3 into several subsections would improve the structural clarity and logical coherence of the manuscript. In the revised version, we divide Section 3 into two subsections: (1) Impact of QBO on Arctic PSCs; and (2) How the QBO influences the Arctic PSC area.

3. The current analysis relies on a single observational dataset (CALIPSO), which has a relatively limited temporal coverage. Are there other PSC observations covering different time periods that could be incorporated? I suggest the authors consider using additional observational datasets to further validate the key conclusion of the manuscript, that PSC occurrence is more frequent during WQBO phases compared to EQBO phases. This would help enhance the robustness and credibility of the findings.

Response: Thank you for your insightful suggestion. The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) observed PSCs over both polar regions from 2002 to 2012 (Spang et al., 2018). 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 R2, 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.

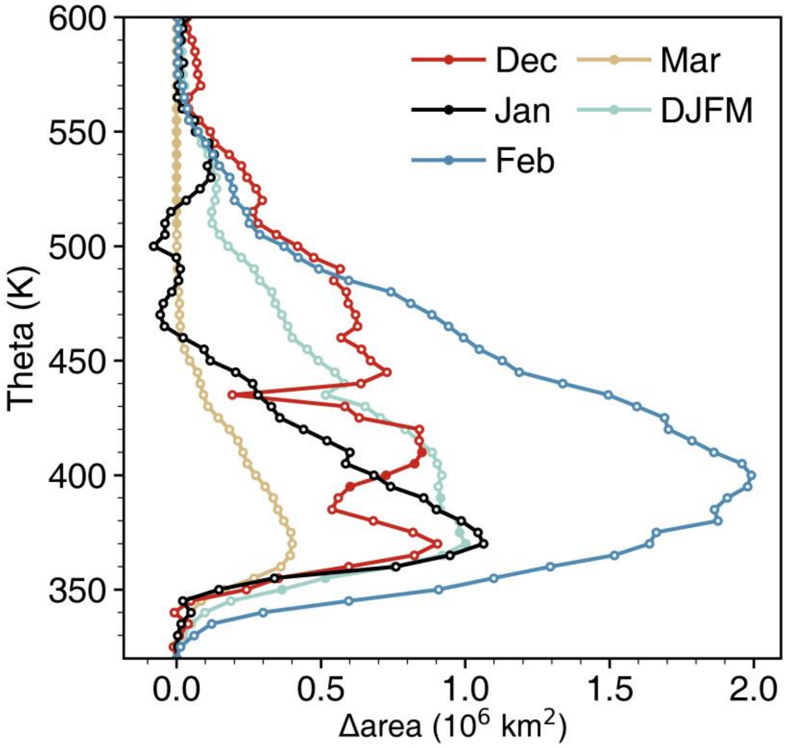

Figure R2. Differences in Arctic PSC area between the WQBO and EQBO phases derived from MIPAS during December–March (DJFM) and the DJFM average. Solid filled symbols indicate the differences are statistically significant at the 95% confidence level according to the Student's *t*-test.

To further support our conclusions, we calculated the PSC volume by vertically integrating the PSC coverage area from CALIPSO, MIPAS, and SLIMCAT. Figure R3 shows the time series of Arctic PSC volume from these three datasets. Due to CALIPSO's higher detection threshold, the observed PSC volume is smaller than those of MIPAS and SLIMCAT. Nevertheless, the interannual variability is remarkably consistent across all three datasets. Table 1 summarizes the PSC volumes during the WQBO and EQBO phases, showing that all three datasets indicate significantly greater PSC volume during the WQBO phase compared to the EQBO phase. Overall, the agreement between satellite observations (CALIPSO and MIPAS) and SLIMCAT simulations provides strong support for the robustness of our key conclusion.

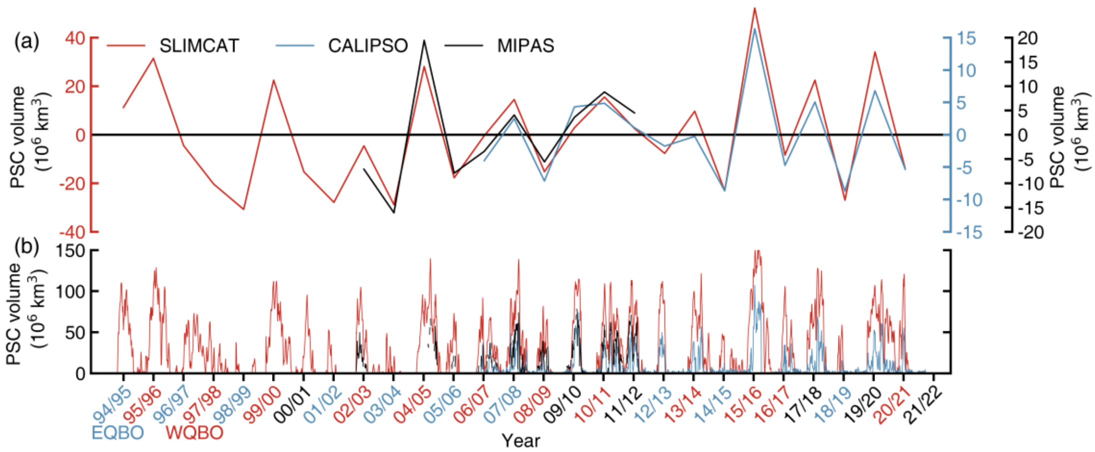

Figure R3. (a) Interannual variation of Arctic PSC volume (December–March mean) anomalies and (b) daily evolution of Arctic PSC volume observed by CALIPSO, MIPAS, and simulated by SLIMCAT. In the horizontal axis, blue and red labels indicate EQBO and WQBO winters, respectively. In panel (a), the different colours on the vertical axis represent different data sources.

Table 1. December–March mean PSC volumes for CALIPSO, MIPAS, and SLIMCAT during WQBO and EQBO phases and differences between the WQBO and EQBO phases (unit: 10^6 km^3). The volumes are calculated over the vertical range of 10–30 km.

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

Specific comments:

P1, L12: analyzes -> examines

Response: Thank you for your comment. Corrected. (Please see P1 and L12 in the revised manuscript)

P1, L13: there is -> there exists

Response: Thank you for your comment. We changed "Previous studies have shown that there is a linear relationship between ozone loss and PSC volume illuminated by sunlight". In the sentence "there is", we have replaced "there is" with "there exists". (Please see P1 and L29 in the revised manuscript)

P1, L27: I would suggest an explanation of Clx.

Response: Thank you for your comment. Cl_x represents reactive chlorine species, including Cl, ClO, Cl_2O_2 which can participate in ozone depletion. We have added a brief explanation of Cl_x in the revised manuscript: (Please see P1 and L27-L28 in the revised manuscript)

"When spring arrives, these reactive chlorine atoms participate in the Cl_x (= Cl + ClO + $2Cl_2O_2$) catalytic cycles that destroy stratospheric ozone (Solomon et al., 1986, 2015)."

P1, L29: Delete the "." after sunlight.

Response: Thank you for your comment. Deleted.

P2, L47: Add a comma after "HNO3".

Response: Thank you for your comment. Added. (Please see P2 and L48 in the revised manuscript)

P2, L49: atmospheric-> atmosphere

Response: Thank you for your comment. Corrected. (Please see P2 and L50 in the revised manuscript)

P3, L69-L70: SSW->SSWs; which have -> which has

Response: Thank you for your comment. Corrected. (Please see P3 and L70-L71 in the revised manuscript)

P4, L22: spans -> span

Response: Thank you for your comment. Corrected. (Please see P4 and L127 in the revised manuscript)

P5, L133: vertical range spanning from 316 to 0.00215 hPa -> vertical range of 316 hPa to 0.00215 hPa; Delete "an".

Response: Thank you for your comment. Corrected. (Please see P5 and L138 in the revised manuscript)

P6, L163: surface density-> surface area density

Response: Thank you for your comment. Corrected. (Please see P6 and L168 in the revised manuscript)

P6, L187: Are the PSC coverage areas of SLIMCAT and CALIPSO daily? You need clarify.

Response: Thank you for your comment. The PSC coverage areas of SLIMCAT and CALIPSO are daily. We have clarified it: (Please see P7 and L193 in the revised manuscript)

"In this study, two different methods are used to calculate the daily PSC coverage areas of CALIPSO and SLIMCAT, respectively."

P8, L215: on 500 K -> on the 500 K

Response: Thank you for your comment. We have modified Figure 1 and deleted "on 500 K".

P8, L221: How do you perform the composite analyses, was it WQBO-EQBO?

Response: Thank you for your question. We calculated the difference between the WQBO and EQBO phases (WQBO minus EQBO). We clarify it in the revised manuscript: (Please see P9 and L240 in the revised manuscript)

"To investigate the relationship between the QBO and PSCs, composite analyses of

PSCs are performed (WQBO minus EQBO).”

P8; L221-222: are removed -> were removed

Response: Thank you for your comment. Corrected. (Please see P9 and L242 in the revised manuscript)

P8, L226: level -> levels

Response: Thank you for your comment. Corrected. (Please see P9 and L245 in the revised manuscript)

P8, L227: differences -> differences in PSC area

Response: Thank you for your comment. Corrected. (Please see P9 and L246 in the revised manuscript)

P8, L228: Why are the differences in the SLIMCAT PSC area larger than those observed by CALIPSO? Does SLIMCAT reproduce the observed PSCs well?

Response: Thank you for your insightful question. The differences in PSC area between the WQBO and EQBO phases are larger in the SLIMCAT simulations than in the CALIPSO observations. This may be since the PSC area of the SLIMCAT is much larger than that of the CALIPSO. There are several factors contributing to the discrepancy between simulated and observed PSCs (Li et al., 2024). First, although CALIPSO has high vertical and horizontal resolution, its limitations in detecting optically thin clouds may lead to an underestimation of the PSC due to the high detection threshold. Second, the lower spatial resolution of SLIMCAT leads to an overestimation of the PSC coverage area.

Although the PSC area and occurrence frequency simulated by SLIMCAT are larger than those observed by CALIPSO, SLIMCAT captures the key features of PSC variability well, including the seasonal cycle, interannual variability, and spatial patterns (Li et al., 2024). In addition, SLIMCAT reproduces well the

enhanced PSC area and occurrence frequency during the WQBO phase compared to the EQBO phase, consistent with CALIPSO observations.

We added this sentence to the manuscript: (Please see P9 and L249-L251 in the revised manuscript)

"The greater differences in SLIMCAT PSC area between the WQBO and EQBO phases primarily result from SLIMCAT simulating larger PSC areas than CALIPSO observations, likely due to CALIPSO's higher detection threshold (Li et al., 2024)."

References:

Li, D., Wang, Z., Li, S., Zhang, J., and Feng, W.: Climatology of Polar Stratospheric Clouds Derived from CALIPSO and SLIMCAT, Remote Sens., 16, 3285, https://doi.org/10.3390/rs16173285, 2024.

P10, L254: zonal asymmetry of -> zonal asymmetry in

Response: Thank you for your comment. Corrected. (Please see P11 and L275 in the revised manuscript)

P10, L255: changes -> shifts

Response: Thank you for your comment. Corrected. (Please see P11 and L276 in the revised manuscript)

P10, L266: that in -> those in

Response: Thank you for your comment. Corrected. (Please see P11 and L287 in the revised manuscript)

P12, L291: during 1979–2022 -> for the period 1979–2022

Response: Thank you for your comment. Corrected. (Please see P13 and L312 in the revised manuscript)

P13, L314: Arctic -> the Arctic

Response: Thank you for your comment. Corrected. (Please see P14 and L336 in the revised manuscript)

P18, L409: strength-> the strength

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