

Reviewer 1

General Comments:

This manuscript investigates the cross-seasonal influence of tropical central Pacific (Niño 4) SST anomalies on the Antarctic stratosphere. While the authors have engaged with some of the previous critique, several major, unresolved issues critically undermine the core findings and conclusions. I cannot recommend the manuscript for publication in its current state.

The principal problems relate to the unverified handling of timescales, the use of improper metrics for non-uniform anomalies, and a misalignment between the observational and model-based analyses. These, combined with an incomplete physical mechanism and persistent technical errors, necessitate a fundamental re-evaluation of the study's methodology.

Reply:

We thank the reviewer for their constructive comments, which have helped improve our the manuscript. In response to the reviewer's concerns, we have made extensive revisions to the manuscript, as detailed below.

Specific Comments:

1. Unsubstantiated claim on timescale filtering. The tropical central Pacific SST and the Antarctic stratospheric indices both exhibit notable decadal-scale variance in Fig. 4. The authors' central claim—that the results are robust after filtering this low-frequency component—is stated without supporting evidence. This claim must be visually and quantitatively demonstrated. A figure directly comparing the key relationships (e.g., regression/correlation maps) using raw data versus interannually filtered data is essential. Without this validation, the paper's primary conclusion lacks a credible foundation.

Reply: To address the reviewer's concern, a 10-year low-pass filter was applied to both the tropical central Pacific SST and the Antarctic stratospheric indices to isolate their decadal components (Fig. R1b). The interannual components were then obtained by subtracting the decadal signals from the original time series (Fig. R1c).

We subsequently calculated correlation coefficients for each component. For the original time series, the correlation coefficient between the tropical central Pacific SST and the Antarctic stratospheric indices is 0.43 ($p < 0.01$) (Fig. R1a). The decadal components exhibit a much stronger correlation of 0.82 ($p < 0.01$), indicating that a pronounced decadal-scale relationship exists between the two indices.

Importantly, however, the interannual components remain significantly correlated, with a correlation coefficient of 0.41 ($p < 0.01$). Although this value is slightly lower compared to that

of the original series, it remains statistically robust, demonstrating the tropical central Pacific SST exerts a significant influence on Antarctic stratospheric temperatures events at interannual timescales.

We have revised Section 7 to reflect these discussions. In particular, we have added the second paragraph to address the influence of the decadal variability on our results.

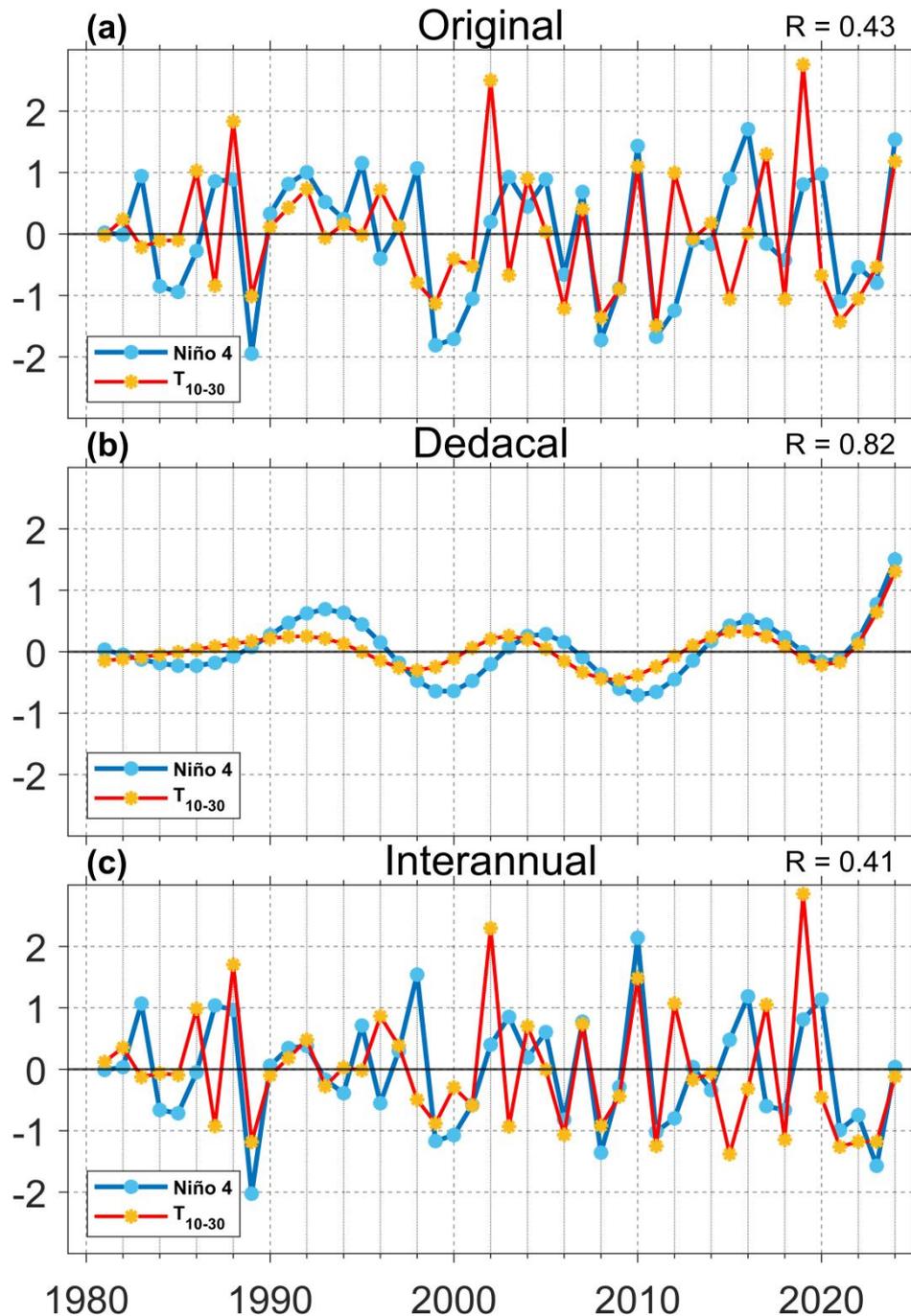


Figure R1. (a) Time series of standardized Niño 4 index (blue line) and the July–September mean T_{10-30} index (red line). Panels (b) and (c) are the same as (a), but show the decadal (b) and interannual (c) components, respectively. The value R in the upper right corner denotes the correlation coefficient between the Niño 4 and the T_{10-30} indices.

2. Use of an inappropriate area-averaged index. Figure 3 clearly shows the stratospheric response is regionally confined (primarily to the Eastern Hemisphere). The authors acknowledge this non-uniformity yet persist in using a mean over the entire Antarctic continent or as their primary stratospheric diagnostic. This averaging method is scientifically unsound, as it dilutes the signal of interest with noise from non-responsive regions. The analysis must be refocused on the region of significant anomalies (e.g., through point-by-point mapping). All subsequent analyses (regressions, model validation) that depend on this flawed index are invalidated until corrected.

Reply: Following the reviewer's comments, we first examine the spatial correlation between the December–February Niño 4 index and the subsequent July–September mean Southern Hemisphere stratospheric temperature. As shown in Fig. R2, the strongest and most statistically significant correlations occur over the region spanning approximately 30°E–160°W and 55°S–75°S.

We then construct a regional stratospheric temperature index (hereafter $T_{10-30 \text{ reg}}$) by averaging temperatures over this region. Figure R3 presents the time series of the Niño 4 index, T_{10-30} , and $T_{10-30 \text{ reg}}$. The correlation between the Niño 4 index and T_{10-30} is $R = 0.43$, while that between the Niño 4 index and $T_{10-30 \text{ reg}}$ is $R = 0.42$.

These results indicate that the significant correlation between the the Antarctic-mean stratospheric temperature index (T_{10-30}) and the Niño 4 index is not diluted by regions with weak or insignificant signals (eg. 120°W–60°W and 55°S–75°S). Moreover, the correlation between T_{10-30} and $T_{10-30 \text{ reg}}$ is very high ($R = 0.93$), demonstrating that the Antarctic-mean index effectively captures the dominant stratospheric warming signal over the dynamically active region.

Taken together, these results suggest that the T_{10-30} index provides a robust and representative diagnostic of Antarctic stratospheric warming in this study. Consequently, the main conclusions and subsequent analyses based on this index, including regression and model validation results, remain valid and are not affected by the choice of averaging domain.

At the beginning of the last paragraph of Section 3, we have added “Following previous studies (Rao et al., 2020; Baldwin et al., 2021; Zi et al., 2025; Lim et al., 2026), the Antarctic stratospheric temperature index (T_{10-30}) is used to examine the stratospheric response. Although the strongest and most statistically significant correlations between the December–February Niño 4 index and the subsequent July–September mean Antarctic stratospheric temperature are found over the region spanning approximately 30°E–160°W and 55°S–75°S (Fig.3), the T_{10-30} index

provides a robust and representative diagnostic of Antarctic stratospheric warming, exhibiting a high correlation coefficient ($R= 0.93$) with the temperature index averaged over $30^{\circ}\text{E}-160^{\circ}\text{W}$ and $55^{\circ}\text{S}-75^{\circ}\text{S}$.”

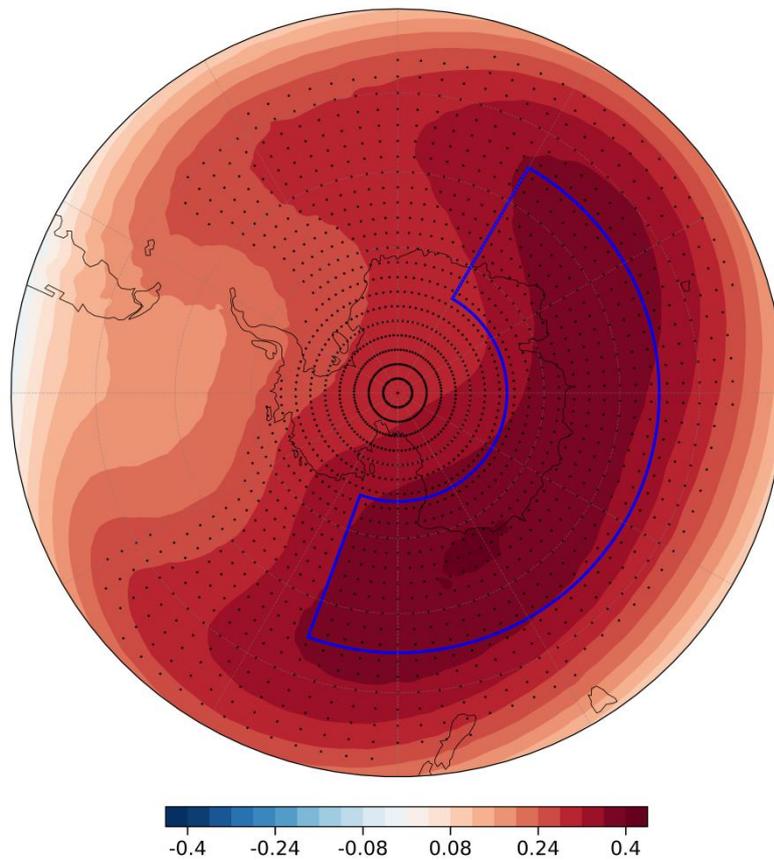


Figure R2. Correlation between the December–February mean Niño 4 index and the July–September mean temperature averaged at 10–30 hPa. Black dots indicate regions statistically significant at the 90% confidence level. Blue box denote the region at $30^{\circ}\text{E}-160^{\circ}\text{W}$ and $55^{\circ}\text{S}-75^{\circ}\text{S}$.

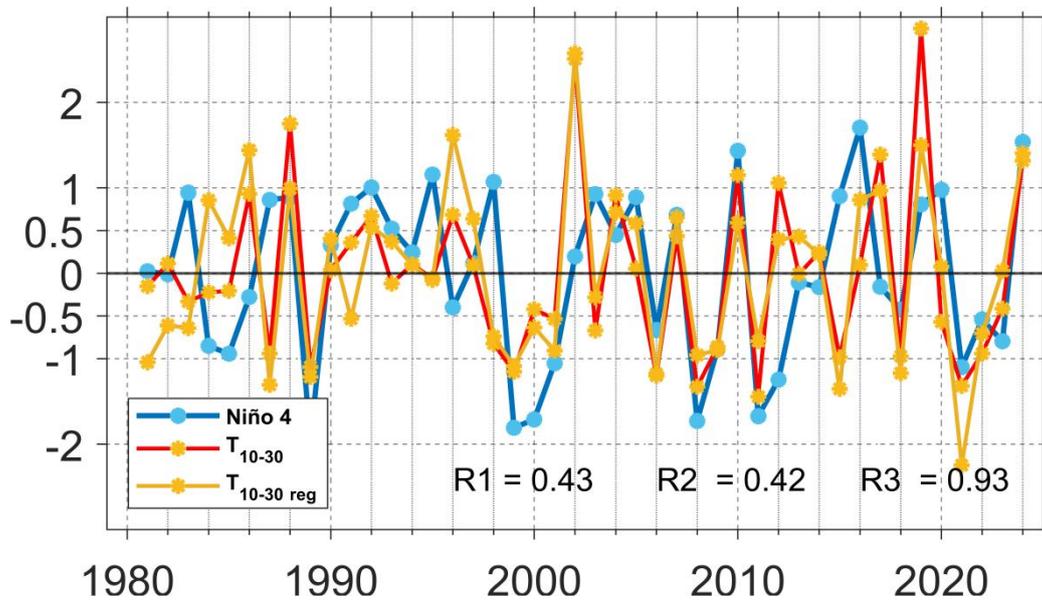


Figure R3. Time series of the standardized Niño 4 index (blue line), the July–September mean T_{10-30} index (red line; averaged over 0° – 360° and 60° S– 90° S) and $T_{10-30 \text{ reg}}$ index (yellow line; averaged over 30° E– 160° W and 55° S– 75° S). R1 and R2 denotes the correlation coefficients between the Niño 4 and the $T_{10-30 \text{ all}}$ and $T_{10-30 \text{ half}}$ indices, respectively. R3 denote the correlation coefficient between the $T_{10-30 \text{ all}}$ and the $T_{10-30 \text{ reg}}$ indices

3. Misapplication of CMIP6 model data. The new analysis of model experiment is good, does not correctly test the hypothesis. The study aims to assess a cross-seasonal influence (tropical SST leading stratospheric response). However, the CMIP6 analysis uses a correlation between January–March SST and July–September T10. This changes the scientific question. This issue also is exacerbated by point #2, as the flawed T10 index is applied to the models. The CMIP6 analysis must be reconfigured to directly mirror the observational lead-lag framework. Furthermore, it should examine the model-simulated spatial pattern of the response related to a Niño 4 index, not the improper T10 average.

Reply: Following the reviewer’s suggestion, the methodology for the CMIP6 analysis has been updated in the revised manuscript to ensure consistency with that for the reanalysis dataset. Specifically, the Niño 4 index is calculated from the CMIP6 historical simulations. Warm and cold years are then identified using a threshold of ± 0.5 standard deviation of the Niño 4 index in each CMIP6 historical simulation, and composite analyses are subsequently performed for relevant variables, including SST, 10 hPa temperature, and Antarctic sea-ice concentration. This revised approach allows for a more consistent and robust assessment of the cross-seasonal linkage between tropical central Pacific SST anomalies and Antarctic stratospheric variability.

The corresponding analyses and results have been incorporated into Section 6 of the revised manuscript, as detailed below:

“To further assess the cross-seasonal effects of tropical central Pacific SSTs on Antarctic stratospheric temperature anomalies, we analyze 24 CMIP6 historical fully coupled model simulations covering the period 1951–2014. For each model, the Niño 4 index is first calculated following the same procedure as used for the observational analysis. Warm and cold Niño 4 years are then identified using a threshold of $\pm 0.5\sigma$. Composite differences between warm and cold years are subsequently constructed for DJF mean SST (Fig. 11), JAS mean 10 hPa temperatures (Fig. 12), JAS mean SST (Fig. 13), and JAS mean Antarctic SIC (Fig. 14).

In the DJF mean SST, significant warm SSTs consistently emerge over the tropical Pacific in all models (Fig. 11). Consistent with the observational results, warm SSTs over the tropical central Pacific during boreal winter are significantly associated with Antarctic stratospheric warming in the subsequent austral winter (Fig. 12). Although the magnitude of the JAS Antarctic stratospheric warming varies among models in the 10 hPa, for example, relatively stronger warming is simulated in CanESM5, CanESM5-1, HadGEM3-GC31-LL, ACCESS-CM2, and MPI-ESM-1-2-HAM (Figs. 12i,j,k,q,x), whereas weaker warming is evident in models such as E3SM-1-1, CNRM-CM6-1, and EC-Earth3-Veg (Figs. 12f,m,o), most models exhibit statistically significant warm anomalies. Moreover, consistent with the observations, the warming signal in most models is predominantly located over the Eastern Hemisphere (Figs. 12 and Figs.3 b-d), with only a few models (e.g., CNRM-CM6-1, FIO-ESM-2-0, and MRI-ESM2-0) showing maxima over the Western Hemisphere (Figs. 12m,t,w).

In addition, the July-September mean SST exhibit a statistically significant positive anomalies over the southeastern Pacific (Fig. 13). Similarly, Antarctic SIC shows pronounced negative anomalies over the Amundsen Sea and Ross Sea sectors (Fig. 14), indicating reduced sea-ice cover. Although a small number of models (e.g., E3SM-2-0, BCC-CSM2-MR, and MPI-ESM-1-2-HAM) display relatively weaker sea-ice reductions (Figs. 14g,r,x), the overall response is consistent across models.

Therefore, these results are consistent with observations and support the presence of a cross-seasonal linkage between tropical central Pacific SST anomalies and Antarctic stratospheric polar temperatures.

4. Incomplete and inaccurate physical mechanism. The manuscript's explanation for mid-latitude air-sea interaction is oversimplified and physically misleading. It incorrectly implies that oceanic forcing in the mid-latitudes operates through the same heat-release dynamics dominant in the tropics. The established literature (e.g., Nakamura et al., 2008; Sampe et al., 2010) highlights that mid-latitude SST anomalies primarily influence the overlying atmospheric circulation via the meridional gradient and feedback of atmospheric transient eddies. The mechanistic discussion must be revised to accurately reflect this fundamental distinction.

Reply: We agree with the reviewer that oceanic forcing in the mid-latitudes operates differently from SST anomalies in the tropics. In particular, mid-latitude SST anomalies influence upper-atmospheric circulation through their effects on local baroclinicity and the feedbacks associated with atmospheric transient eddies.

Indeed, our results are consistent with previous studies. For example, previous studies have demonstrated that sea-ice reduction can induce strong upward turbulent heat fluxes from the ocean to the atmosphere, particularly during autumn and winter when air-sea temperature contrasts are large (e.g., Yang et al., 2016). These heat fluxes can reach several hundred W m^{-2} over newly exposed open water, and have been shown to play a critical role in modifying the lower-tropospheric thermal structure and in exciting quasi-stationary Rossby wave responses (Honda et al., 2009; Kim et al., 2014).

Moreover, Kim et al. (2014) and Hoshi et al. (2017) demonstrated that enhanced turbulent heat fluxes associated with Arctic sea-ice loss lead to positive mid-tropospheric geopotential height anomalies and the development of large-scale wave-like circulation patterns. These anomalies are accompanied by upward and poleward propagation of stationary Rossby wave activity, which can extend into the stratosphere and weaken the stratospheric polar vortex. Nakamura et al. (2015) further showed that such Rossby wave responses originate from regions of strong surface heat flux anomalies near the sea-ice edge and propagate preferentially along climatological waveguides, highlighting the importance of background flow and eddy-mean flow interactions.

We have revised Section 4.2.2 by incorporating relevant conclusions from previous studies to better support the physical interpretation.

- (1) In the first paragraph, we have stated “As the amplitude of Niño 4 SST anomalies declines, the accumulated heat in the southeastern Pacific is gradually released (Fig. 8o). This heat is transported upward by atmospheric transient eddies and planetary waves generated by enhanced local baroclinicity in the lower tropospheric, thereby influencing upper-atmospheric circulation (Nakamura et al., 2008; Sampe et al., 2010). Consequently,

a pronounced positive geopotential height anomaly associated with the PSA pattern persists over this region (Fig. 5l).”

- (2) At the end of the third paragraph of Section 4.2.2, we have added “In addition, the enhanced heat in the lower troposphere is transported upward, sustaining the positive geopotential height anomaly through the upward displacement of isobaric surfaces (Fig. 8c), consistent with previous studies (Honda et al., 2009; Kim et al., 2014; Yang et al., 2016; Hoshi et al., 2017).”
- (3) In the last paragraph, we have also added “Moreover, near-surface heating associated with sea-ice loss acts as an effective source of planetary-scale wave activity under wintertime background conditions, contributing to the amplification of zonal wave patterns and enhanced planetary wave propagation (Kim et al., 2014; Nakamura et al., 2015).”

- [1] Kim, B.-M., Son, S.-W., Min, S.-K., Jeong, J.-H., Kim, S.-J., Zhang, X., et al.: Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nature Communications*, 5(1). <https://doi.org/10.1038/ncomms5646>, 2014.
- [2] Hoshi, K., Ukita, J., Honda, M., Iwamoto, K., Nakamura, T., Yamazaki, K., et al.: Poleward eddy heat flux anomalies associated with recent Arctic sea ice loss. *Geophysical Research Letters*, 44(1), 446–454. <https://doi.org/10.1002/2016gl071893>, 2017.
- [3] Honda, M., Inoue, J., and Yamane, S.: Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. *Geophysical Research Letters*, 36(8). <https://doi.org/10.1029/2008gl037079>, 2009.
- [4] Yang, X.-Y., Yuan, X., and Ting, M.: Dynamical Link between the Barents–Kara Sea Ice and the Arctic Oscillation. *Journal of Climate*, 29(14), 5103–5122. <https://doi.org/10.1175/jcli-d-15-0669.1>, 2016.
- [5] Nakamura, T., Yamazaki, K., Iwamoto, K., Honda, M., Miyoshi, Y., Ogawa, Y., and Ukita, J.: A negative phase shift of the winter AO/NAO due to the recent Arctic sea-ice reduction in late autumn. *Journal of Geophysical Research: Atmospheres*, 3209–3227. <https://doi.org/10.1002/2014jd022848>. 2015.

5. Persistent technical errors and lack of polish. Inconsistent notation remains (e.g., the use of '*' and 'x' in equations (3) and (4) needs clarification and uniformity). Text duplication exists (e.g., lines 541-542 vs. 546-548). A meticulous, line-by-line review of the entire manuscript is necessary to correct typographical errors, ensure notational consistency, and improve overall

clarity before any future submission.

Reply: We have revised the manuscript to correct typographical errors, ensure notational consistency, and eliminate duplicated text. In addition, a thorough line-by-line review was conducted to improve clarity and the overall presentation of the manuscript.

Reviewer 2

The authors have addressed most of my concerns and comments. However, the manuscript requires thorough proofreading to correct numerous grammatical errors, awkward phrasings, and syntactical issues to improve its clarity and readability for an international audience.

Reply:

We thank the reviewer for their encouragement. In response to the reviewer's concerns, we have conducted a thorough proofreading of the entire manuscript to improve clarity and readability. In addition, to clearly illustrate the physical pathway through which boreal winter tropical central Pacific SST anomalies influence the Antarctic stratosphere in the subsequent austral winter, we have added a conceptual schematic (Fig. 16) that summarizes the key dynamical and thermodynamical processes involved, and we have included a detailed explanation of this schematic in Section 7.

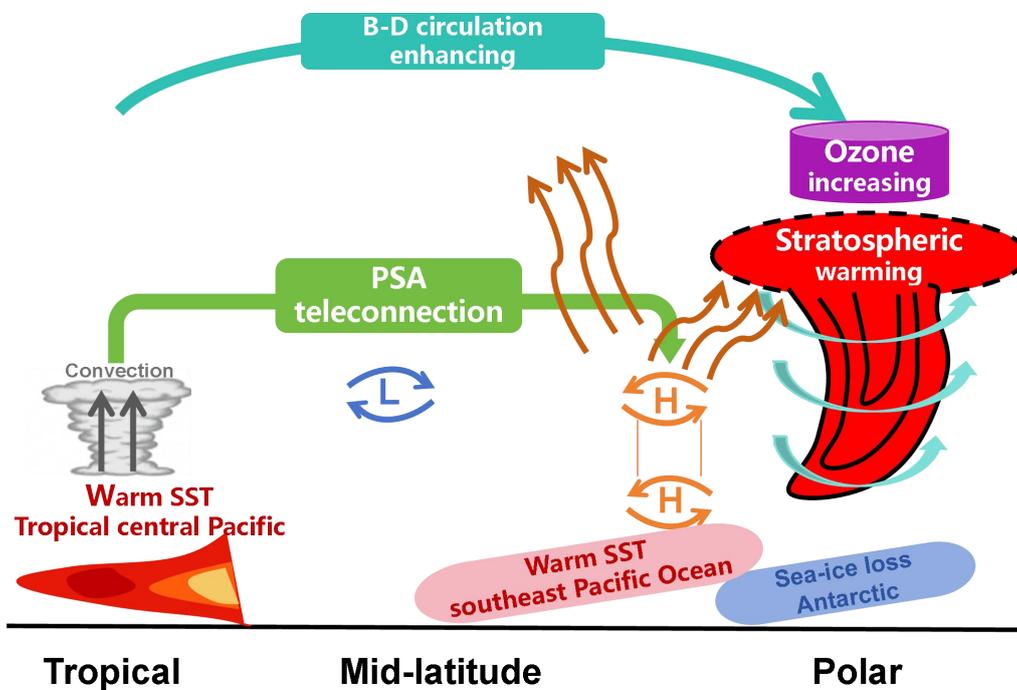


Figure 16. Schematic diagram of the proposed physical mechanism linking boreal winter Niño 4 SST anomalies to austral winter Antarctic stratospheric warming.

The authors missed some latest and highly relevant research regarding the impacts of the SST and sea ice in the Southern Hemisphere on the Antarctic stratospheric polar vortex (e.g., Hu et al.; 2022; Song et al., 2025). I strongly suggest adding them in the Introduction.

Reply: Done

References:

Hu, Y., Tian, W.: Weakening of Antarctic stratospheric planetary wave activities in early austral spring since the early 2000s: a response to sea surface temperature trends, *Atmos. Chem. Phys.*, 22, 1575–1600, <https://doi.org/10.5194/acp-22-1575-2022>, 2022.

Song, J., et al. Impact of Early Winter Antarctic Sea Ice Reduction on Antarctic Stratospheric Polar Vortex, *JGR Atmospheres*, 130, e2024JD041831, <https://doi.org/10.1029/2024JD041831>, 2025.

Article Usage

There is a frequent omission of the definite article "the."

- Example (Lines 30 - 31): "...SST anomalies in the Niño4 region during December–February..." (Correction: add "the")

Reply: Done

- Example (Lines 85 - 86): "It also modulates the SPV primarily via the Pacific–North America (PNA) and the Pacific–South America (PSA) wave trains..." (Correction: add "the" before "Pacific–South America" for consistency)

Reply: Done

Awkward Phrasings and Word Choice

- Example (Lines 31 - 33): "...enhanced (suppressed) polar ozone concentrations during July–September of the subsequent year."

Suggestion: "...enhanced (suppressed) polar ozone concentrations in the subsequent July–September period."

Reply: Done

- Example (Line 215): "...associated with warm (cold) central Pacific SSTs."

Suggestion: "...associated with warm (cold) SSTs in the central Pacific."

Reply: Done

- Example (Lines 308 - 309): "...which disturb the SPV through wave–mean flow interactions..."

Suggestion: "...which disturb the SPV through wave-mean flow interactions..." (The en - dash is more standard here than the em - dash).

Reply: Done

Sentence Structure and Clarity

- Example (Lines 34 - 36): "This delayed response is mediated by a Pacific–South America (PSA) teleconnection, which excites planetary waves that propagate upward into stratosphere and modify the Brewer–Dobson circulation."

Suggestion: "This delayed response is mediated by the Pacific–South America (PSA) teleconnection pattern, which excites planetary waves that propagate upward into the stratosphere, thereby modifying the Brewer–Dobson circulation."

Reply: Done

- Example (Lines 426 - 427): "In JAS, surface heat flux is largely associated with sea - ice loss in the Amundsen and Ross Seas..."

Suggestion: "During JAS, the surface heat flux is largely driven by sea - ice loss..." (This is more active and precise).

Reply: Done

Subject - Verb Agreement and Tense

- Example (Line 50): "Furthermore, the Antarctic stratosphere plays a crucial role..." (This is correct).

Ensure consistency in verb tenses, particularly in the description of results (which are generally in the past tense, e.g., "was observed," "showed") and established knowledge (which is in the present tense, e.g., "plays a role").

Reply: Done

Minor Typographical Issues

- Line 156: Equation (1) appears wrong. Please double-check it.

Reply: Equation (1) is correct. In our notation, the zonal-mean is denoted by square brackets $[\]$ rather than an overbar; we have clarified this definition in the text.

- Line 399: "...the negative net heat flux anomaly, defined as the sum of latent and sensible heat fluxes, long-wave radiant and short - wave radiant heating..." should likely be "...long-wave radiation, and short - wave radiation."

Reply: Done