

Comments to Authors:

This study investigates the modulatory effect of the Eurasia-shifted stratospheric polar vortex (ESSPV) on winter extreme precipitation over South China (SC), with a particular focus on the phase-locking role of the Madden–Julian Oscillation (MJO). The authors identify that the statistically weak SPV–extreme precipitation linkage at the seasonal mean scale is strongly amplified during MJO phases 2–5, and propose two synergistic dynamical pathways (high-latitude Rossby wave train and low-latitude moisture transport amplified by the westerly quasi-biennial oscillation). The CMIP6 multi-model analysis further confirms that the fidelity of the MJO-associated western North Pacific anticyclone determines the model’s ability to reproduce the observed linkage.

Overall, this is a well-designed, logically coherent study with clear scientific novelty. It addresses the long-standing puzzle of why the SPV shows a weak and unstable statistical relationship with extreme precipitation in southern China, and provides a physically meaningful explanation from the perspective of intraseasonal–interannual scale interaction. The manuscript uses multiple datasets and model simulations to cross-validate the conclusions, and the findings have important implications for subseasonal-to-seasonal prediction of winter extreme precipitation in East Asia. I recommend publication in ACP after minor-to-moderate revisions to address the following comments.

Response: We deeply appreciate the reviewer for these positive and encouraging comments. These comments are all valuable and helpful for improving our article, which have been fully considered in the revised manuscript. In the paragraphs that follow, we include point-to-point responses:

Major Comments

1. The ESSPV index is defined as the regionally averaged 50-hPa geopotential height anomaly over the Eurasian sector. A negative anomaly in this sector could reflect either (a) a longitudinal displacement of the vortex toward Eurasia, or (b) a general intensification of the vortex with a spatially uniform height decrease. The manuscript frames the phenomenon as a "shift" (Eurasia-shifted SPV), but the index itself does not isolate displacement from intensity. Please add a brief justification or diagnostic showing that the index primarily captures longitudinal displacement rather than a zonally symmetric intensification.

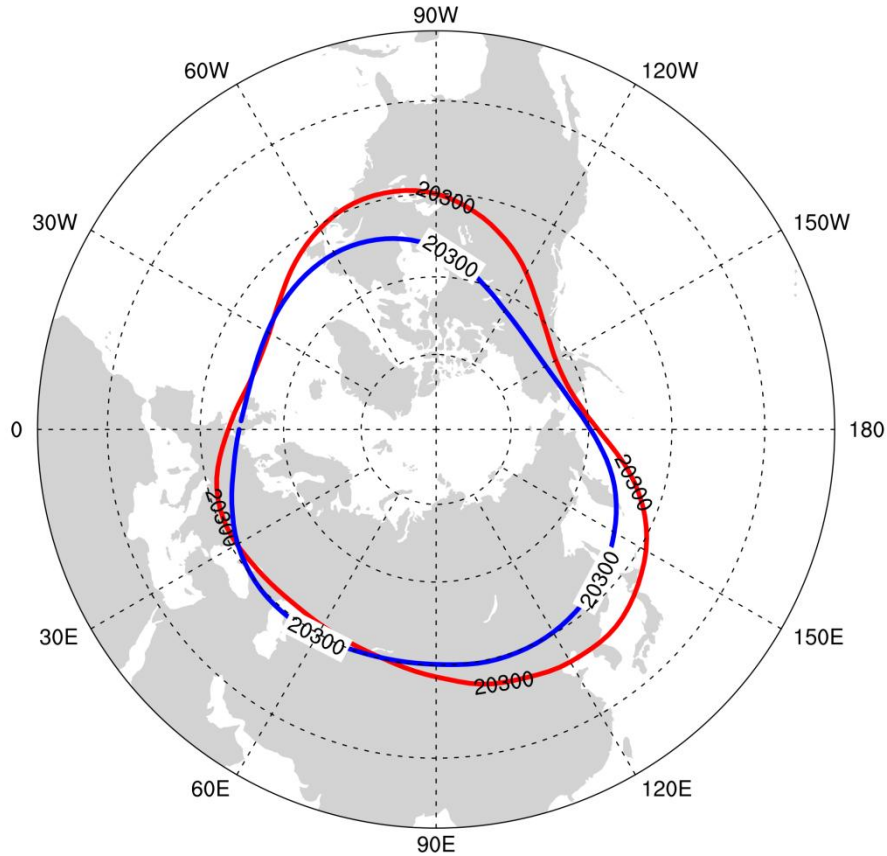
Response: We thank the reviewer for raising this important methodological point. We fully agree that the ESSPV index, defined as the area-averaged 50-hPa geopotential height anomaly over the Eurasian sector (50° – 80° N, 20° – 100° E), does not by itself distinguish between a genuine longitudinal shift of the polar vortex and a uniform intensification of the vortex. To address this concern, we have conducted the following discussion.

First, we examined the spatial pattern of the 50-hPa geopotential height anomalies associated with the ESSPV index. As shown in Fig. 1a of our manuscript, the negative height anomalies are not zonally symmetric but are instead concentrated over the Eurasian sector, with the core of the anomaly centered near the Ural Mountains (approximately 50° – 70° N, 40° – 80° E). Meanwhile, positive or near-normal height anomalies are observed over the North American and Atlantic sectors. This dipole-like pattern, rather than a uniform negative anomaly across all longitudes, is characteristic of a longitudinal displacement of the polar vortex toward the Eastern Hemisphere, rather than a purely symmetric intensification.

Second, we note that the regression patterns shown in Fig. 1b–d, particularly the downstream Rossby wave train and the anomalous anticyclone over eastern Siberia, are dynamically consistent with a displaced vortex configuration. A zonally symmetric intensification would not produce the same asymmetric wave response over Eurasia.

Third, we further add a diagnostic figure in the appendix to visually verify this interpretation (see Supplementary Figure 2). We derive two 50-hPa geopotential height fields by adding and subtracting the regressed anomaly pattern (shading in Fig. 1a) to or from the 50-hPa climatological mean, representing the two typical SPV states (ESSPV/EWSPV). The two resulting contours show a clear east–west longitudinal shift of the polar vortex, rather than a zonally uniform contraction or expansion. This visual evidence directly confirms that our ESSPV index primarily captures the longitudinal displacement of the SPV instead of a symmetric intensification.

We believe that the above analysis fully explains why the ESSPV index defined in this paper primarily reflects the longitudinal displacement of the SPV, rather than a zonally symmetric intensification



Supplementary Fig. 2. Diagnostic diagram of the longitudinal displacement of the stratospheric polar vortex. Red (blue) contours denote 50- hPa geopotential height derived by subtracting (adding) the shading in Fig. 1a from (to) the 50- hPa climatological mean (unit: gpm)

2. The analysis identifies 13 ESSPV and 13 EWSPV winters. When these are further stratified by MJO phases 2–5, the effective number of MJO-phase days within each SPV category becomes relatively small. The composite and probability-density analyses in Figs. 2 and 3 rely on these stratified samples. Please briefly comment on the effective sample size and the robustness of the significance tests under this stratification. Specifically, it would be helpful to state (i) approximately how many MJO phases 2–5 days are composited in each SPV category, and (ii) whether the significance tests account for the reduced degrees of freedom due to autocorrelation within MJO events. A short note in Section 2.2 or the figure captions would address this concern.

Response: We appreciate the reviewer’s careful consideration of the statistical robustness of the composite analysis. We agree that the effective sample size should be explicitly discussed because MJO events exhibit temporal persistence, and treating

individual days as completely independent samples may overestimate statistical significance.

Regarding question (i): In the revised manuscript, we have added the approximate number of MJO phase 2–5 days included in each SPV category. Specifically, after applying the MJO amplitude criterion (RMM amplitude > 1), the ESSPV and EWSPV composites contain approximately 517 and 755 MJO phase 2–5 days, respectively.

Regarding question (ii): the significance tests presented in our study, specifically the composite Student's t-tests used in Figs. 2 and 3, are performed using the raw daily sample sizes (i.e., the total number of days falling into MJO phases 2–5), and thus they don't explicitly apply a reduced-degree-of-freedom correction to account for the autocorrelation intrinsic to MJO events. We fully acknowledge the reviewer's physical concern that the MJO is a slowly evolving, 30–60-day phenomenon, so consecutive days within the same MJO phase are not fully independent. We would like to clarify why we chose to adhere to the standard (uncorrected) approach, for the following reasons:

(1) Nature of the predictand – extreme precipitation as a synoptic-scale event.

Our study focuses on extreme precipitation (R90, daily rainfall exceeding the 90th percentile), which is a high-frequency, synoptic-to-sub-synoptic weather process. Although the MJO provides the large-scale intraseasonal background that modulates the probability of such extremes, the actual occurrence of an extreme rainfall event on any given day is sporadic and does not occupy every consecutive day within a 30–60-day MJO phase window. In other words, the effective persistence of the extreme-rainfall target is much shorter than that of the MJO envelope itself. Therefore, treating each day as an independent sample in the context of extreme event statistics is a commonly accepted simplification in this type of composite analysis.

(2) Consistency with established literature.

We have carefully reviewed the published studies that examine the MJO-phase dependence of winter rainfall over southern/eastern China—including Chen et al. (2020) and Zheng et al. (2020)—both of which employ standard composite Student's t-tests without explicitly reducing the degrees of freedom for day-to-day autocorrelation within the same MJO phase. Our methodological choice is therefore consistent with the prevailing practice in this specific research field, ensuring direct comparability with prior benchmark studies.

Following the reviewer's constructive suggestion, we will add a brief remark in the captions of Figs. 2 and 3 to state (see Lines 257–259 and Lines 295–297): “The

composite significance tests are based on the raw daily sample sizes (517 days for ESSPV and 755 days for EWSPV during MJO phases 2–5). We do not apply a reduced-degree-of-freedom correction.” We believe this revision fully addresses the reviewer’s concern, while transparently documenting our methodological choice and its precedent in the literature.

References

1. Chen, X., Li, C., Li, L., Yu, P., & Yang, M. (2020). Interannual variations of the influences of MJO on winter rainfall in southern China. *Environmental Research Letters*, 15(11), 114011.
2. Zheng, Y., Zhang, Q., Luo, M., Sun, P., & Singh, V. P. (2020). Wintertime precipitation in eastern China and relation to the Madden-Julian oscillation: Spatiotemporal properties, impacts and causes. *Journal of Hydrology*, 582, 124477.

3. The authors regress out the linear Niño3.4 signal from all variables (Section 2.2) and note that the ESSPV index correlates with Niño3.4 at only -0.17 (Section 3). This is a reasonable and standard approach. However, ENSO is known to nonlinearly modulate both the MJO (e.g., MJO amplitude and propagation differ between El Niño and La Niña) and the SPV (e.g., El Niño favors a weakened vortex). A brief sensitivity test or discussion would be valuable: does the MJO-phase-dependent SPV–precipitation linkage persist when strong ENSO winters are excluded entirely?

Response: We thank the reviewer for this thoughtful suggestion. We agree that while linear removal of the Niño3.4 signal is a standard and defensible approach, ENSO’s nonlinear influences on both the MJO and the SPV warrant additional scrutiny. To address this, we have conducted a sensitivity test by excluding all strong ENSO winters from our analysis.

Following the widely used definition, we identified strong El Niño winters ($\text{Niño3.4} \geq 1.5^\circ\text{C}$) and strong La Niña winters ($\text{Niño3.4} \leq -1.5^\circ\text{C}$) during our analysis period (1979–2022). This resulted in the exclusion of the following winters:

Strong El Niño: 1982/83, 1986/87, 1991/92, 1997/98, 2009/10, 2014/2015, 2015/16 (7 winters)

Strong La Niña: 1988/89, 1998/99, 1999/2000, 2007/08, 2010/11, 2020/21, 2021/22 (7 winters)

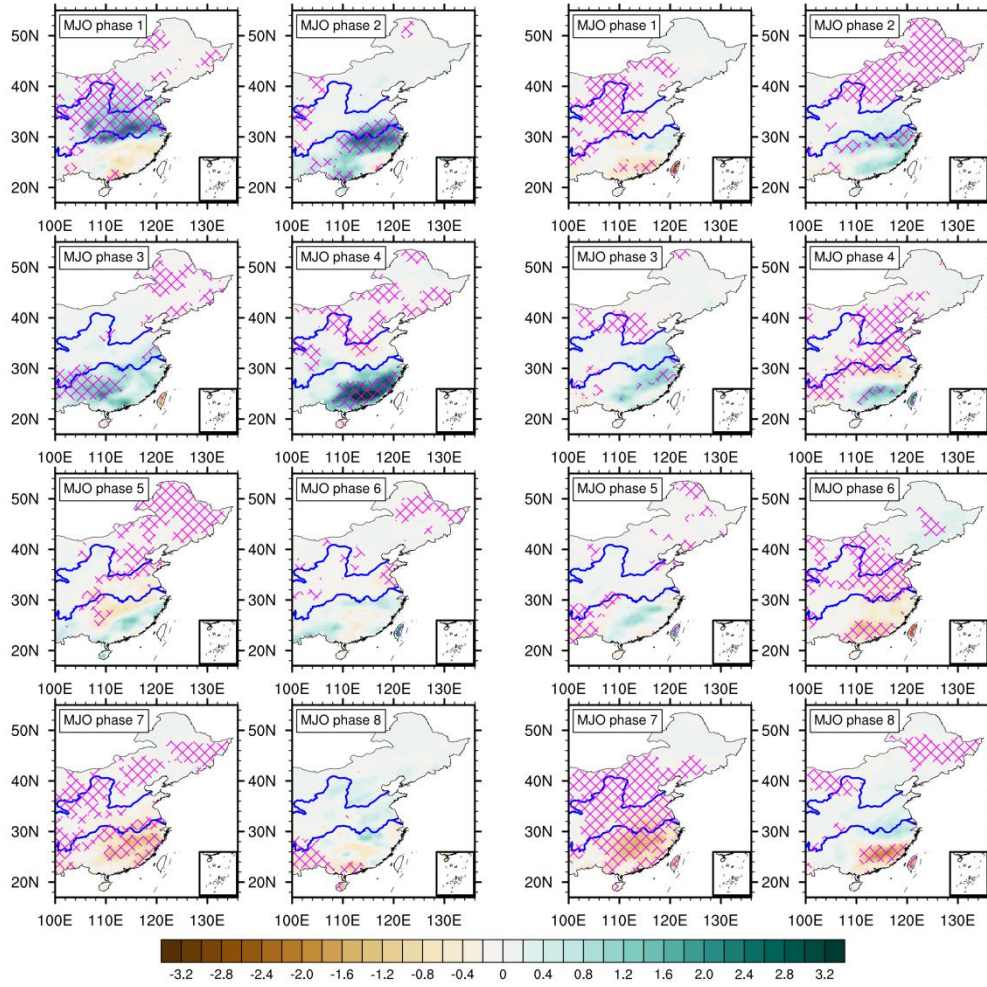
After excluding these 14 strong ENSO winters, we re-performed the key analyses:

The MJO-phase-dependent composite analysis (Fig. 2b in the original manuscript) was repeated using only the neutral-to-weak ENSO winters (see Supplementary Fig.

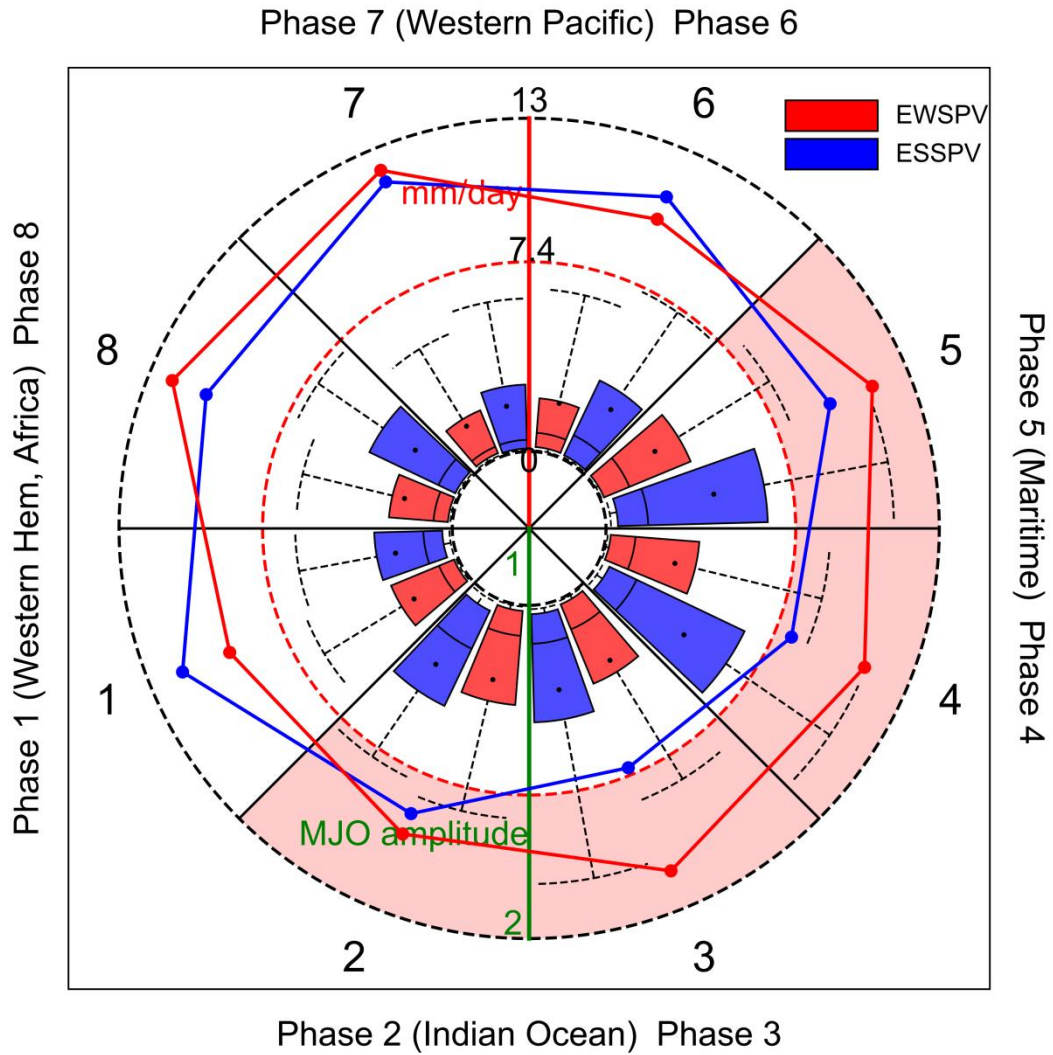
10). The results show that the ESSPV-induced enhancement of SC precipitation during MJO phases 2–5 remains clearly evident, with a very similar magnitude to the full-dataset composites. During MJO phases 6–8 and 1, no consistent enhancement is observed, consistent with our original findings.

The probability density distributions (Fig. 2c in the original manuscript) were also re-computed (see Supplementary Fig. 9). The 90th, 75th, and 50th percentiles of SC daily precipitation during MJO phases 2–5 remain significantly higher in ESSPV winters than in EWSPV winters, even after excluding strong ENSO years.

These sensitivity results confirm that our main findings are not driven by strong ENSO events and that the MJO-phase-dependent SPV–precipitation linkage is robust across different ENSO backgrounds. We will incorporate this discussion into the revised Section 4 (see Lines 241–244), along with two new supplementary figures (Supplementary Fig. 8 and Fig. 9) showing the sensitivity results: “To eliminate the nonlinear influence of strong ENSO winter events on SPV events, we conducted sensitivity tests; after excluding 14 strong ENSO events, the relationship between SPV events and extreme precipitation still exhibited a dependence on the MJO phases (Supplementary Fig. 8 and Fig. 9).” We note that the total number of ESSPV and EWSPV winters identified in the neutral-to-weak ENSO subset is reduced (8 ESSPV winters and 9 EWSPV winters), which inevitably reduces the statistical power. Nevertheless, the consistent signals across both the full and the ENSO-excluded datasets give us confidence in the robustness of our conclusions.



Supplementary Fig. 8. Precipitation responses under the synergistic impacts of ESSPV and MJO after excluding 14 strong ENSO events. Following the widely used definition, we identified strong El Niño winters ($\text{Niño}3.4 \geq 1.5^\circ\text{C}$) and strong La Niña winters ($\text{Niño}3.4 \leq -1.5^\circ\text{C}$) during our analysis period (1979–2022): strong El Niño: 1982/83, 1986/87, 1991/92, 1997/98, 2009/10, 2014/2015, 2015/16 (7 winters), strong La Niña: 1988/89, 1998/99, 1999/2000, 2007/08, 2010/11, 2020/21, 2021/22 (7 winters). Composite evolution patterns of MJO phases 1–8 precipitation anomalies (unit: mm day^{-1}) associated with 8 ESSPV (left) and 9 EWSPV (right) winters. Meshes indicate significant precipitation anomalies at the 95% confidence level.



Supplementary Fig. 9. Probability density distributions of daily precipitation in SC during MJO phases 1–8 in 7 ESSPV (blue box) and 8 EWSPV (red box) winters after excluding 14 strong ENSO events. Following the widely used definition, we identified strong El Niño winters ($\text{Niño}3.4 \geq 1.5^\circ\text{C}$) and strong La Niña winters ($\text{Niño}3.4 \leq -1.5^\circ\text{C}$) during our analysis period (1979–2022): strong El Niño: 1982/83, 1986/87, 1991/92, 1997/98, 2009/10, 2014/2015, 2015/16 (7 winters), strong La Niña: 1988/89, 1998/99, 1999/2000, 2007/08, 2010/11, 2020/21, 2021/22 (7 winters). The box bounds indicate the 10th, 25th, 50th, 75th, and 90th percentiles, and dots indicate the mean. The solid dot octagons denote the average amplitude of MJO in 8 ESSPV (blue) and 9 EWSPV (red) winters. The red dashed line indicates the wintertime 90th percentile threshold for SC precipitation (about 7.4 mm day^{-1}).

4. Section 3 states that "10 out of 13 ESSPV winters correspond to the westerly QBO (WQBO) phase" and invokes the "Holton–Tan framework." The classic Holton–Tan effect describes how the easterly QBO phase weakens the polar vortex (and the westerly phase strengthens it) via modulation of planetary wave propagation. The manuscript's finding that ESSPV (a shifted, presumably stronger-over-Eurasia vortex) is associated with WQBO is broadly consistent with Holton–Tan, but the directional

logic could be stated more explicitly.

Response: We thank the reviewer for this important clarification. We agree that the directional logic of the Holton–Tan coupling in our context could be stated more explicitly, and we appreciate the opportunity to refine this discussion.

The classic Holton–Tan (1980) effect describes how the easterly QBO (EQBO) phase favors a weakened stratospheric polar vortex through enhanced planetary wave propagation from the troposphere into the stratosphere, while the westerly QBO (WQBO) phase favors a strengthened polar vortex due to reduced wave propagation. In the context of our study, the ESSPV—characterized by a deepened vortex over the Eurasian sector—represents a regionally intensified polar vortex configuration over the Eastern Hemisphere. The fact that 10 out of 13 ESSPV winters correspond to the WQBO phase is therefore dynamically consistent with the Holton–Tan framework: the WQBO tends to strengthen the polar vortex, which in our regional diagnostic manifests as a more negative geopotential height anomaly over Eurasia (i.e., the ESSPV pattern).

However, we acknowledge that the causal direction in our manuscript could be misread. We do not claim that the ESSPV causes the WQBO; rather, we interpret the WQBO as providing a favorable background state that co-occurs with and supports the ESSPV configuration via the Holton–Tan mechanism. The WQBO modulates the stratospheric background flow in a way that favors a stronger and more displaced polar vortex over Eurasia, which in turn sets the stage for the tropospheric responses we document.

To make this directional logic clearer, we will revise the relevant paragraph in Section 3 as follows (see Lines 160-167): "Under the Holton–Tan framework, the westerly phase of the QBO (WQBO) is known to favor a stronger polar vortex by suppressing planetary wave propagation into the stratosphere, whereas the easterly phase (EQBO) favors a weaker vortex. Consistent with this paradigm, we find that 10 out of 13 ESSPV winters correspond to the WQBO phase, while 9 out of 13 EWSPV winters correspond to the EQBO phase (Supplementary Table 1). This suggests that the WQBO provides a stratospheric background state that is conducive to the development of a deepened polar vortex over the Eurasian sector...." We believe this revision more accurately reflects the directional logic of the Holton–Tan framework and clarifies that the WQBO is interpreted as a supporting background condition rather than a direct driver of the ESSPV.

Minor Comments

- (1) Line 20: "its stratospheric drivers remain limited understood" to "limitedly understood"
- (2) Line 22: "a Eurasia-shifted SPV" to "an Eurasia-shifted SPV"
- (3) Line 66: "the SPV–extreme rainfall relationship is statistically weak and unstable in the climatological sense". Considering "in the climatological-mean sense" for precision.
- (4) Line 43: The Introduction cites the "April 2024 extensive flood" as a winter precipitation extreme (Section 1). April is outside the NDJFM winter window used in the analysis. While April can still experience winter-like circulation systems, using it as a motivating example for "winter extreme precipitation" may confuse readers.
- (5) Lines 104-105: The phrase "Quadratic linear trends were removed" is internally contradictory. A quadratic trend is not linear.
- (6) Figure 1b uses wave activity flux vectors, but the Takaya and Nakamura (2001) formulation is not cited in the main text (it appears only in the References). Please add a citation in the figure caption or methods where the flux is first introduced.
- (7) Lines 230-231: "This 'weaker MJO intensity–stronger extreme precipitation' paradox firmly establishes that...". The word "firmly" may be too strong given the observational constraints. Suggest: "This 'weaker MJO intensity–stronger extreme precipitation' paradox indicates that..."

Response: We thank the reviewer for the careful reading and the thoughtful minor comments. We have accepted all suggestions and made the corresponding revisions in the revised manuscript. Below we detail how each point has been addressed:

- (1) Line 20 ("its stratospheric drivers remain limited understood"): Corrected to "limitedly understood" for grammatical accuracy.
- (2) Line 22 ("a Eurasia-shifted SPV"): Changed to "an Eurasia-shifted SPV" to follow standard English phonetics.
- (3) Line 66 ("in the climatological sense"): Revised to "in the climatological-mean sense" to more precisely refer to the winter-mean background state.
- (4) Line 43 ("April 2024 extensive flood" as a winter extreme): We recognize that April falls outside our NDJFM analysis window. To avoid confusion, we have deleted this incident.
- (5) Lines 104–105 ("Quadratic linear trends were removed"): We have corrected this contradictory phrasing to "Quadratic trends were removed" (the method we actually applied) (see Line 103).

(6) Figure 1b (wave activity flux): We have added a citation to Takaya and Nakamura (2001) in the figure caption and also in the Methods section where the wave-activity flux is first introduced (now explicitly cited alongside the formula).

(7) Lines 230–231 (“firmly establishes”): As suggested, we have softened the wording to “indicates” to better reflect the observational constraints, while keeping the scientific conclusion unchanged (see Line 237).

All changes have been marked in the revised manuscript. We are grateful for these constructive suggestions, which have improved the clarity and precision of our paper.