Referee #1:

General comments:

The manuscript by Luo et al. investigates the impacts of Asian sulfate aerosols on regional summer extreme precipitation and their underlying physical mechanisms using the reduced-complexity climate model FORTE2. The authors compare a suite of SyRAP-FORTE2 simulations under two different background climate states (piC and p1K) with different aerosol treatments, and further compare their findings against the PDRMIP multi-model simulations. The results demonstrate that sulfate aerosols generally suppress extreme precipitation across some Asian regions, primarily driven by large-scale dynamic effects, and that a warmer climate background enhances this suppression by increasing lower-tropospheric static stability. The study also suggests a linear ARI-ACI combination under pre-industrial conditions and nonlinear interactions under a +1K climate.

The topic falls within the scope of ACP and holds scientific value. The experiments are well designed, and the paper is generally written in a clear way. However, the Abstract and Conclusion need to be more concise and focused to effectively convey the core findings and broader implications. Furthermore, several methodological and analytical details require clarification. Therefore, I recommend a major revision before its final publication.

Thank you very much for your time and for your insightful and constructive comments on our manuscript. Your feedback has been invaluable in helping us improve the quality of this work. We have carefully addressed each comment on a point-by-point basis and hope that our revisions and responses now meet with your approval. The main changes to the manuscript and our detailed point-by-point responses are outlined below.

A general suggestion for plots: Please maintain consistency in the colorbars throughout the paper. For instance, blue represents positive values in Figs. 4, 7, 9, 11, 13 but negative values in other figures, which may confuse readers.

Response: Thank you for this helpful suggestion, and we apologize for any confusion caused. We have revised the color bars as follows: for figures related to precipitation response (Figs. 4, 7, 11, and 13), a yellow-green colorbar is used, with green indicating an increase in precipitation and yellow indicating a decrease. For all other figures, the red-blue colorbar has been retained, with red representing positive values and blue representing negative values.

Specific comments:

Line 23: The Abstract should begin with a brief background and introduction to the topic, followed by a clear statement of the main scientific challenges/gaps and research questions this study aims to address.

Response: Thank you for pointing out this issue. We have revised the opening sentence of the Abstract to briefly introduce the background and clearly state the main scientific gap addressed in this study. The revised sentence: "Extreme precipitation threatens ecosystems and human safety, yet how Asian sulfate aerosols differently influence regional summer extreme precipitation under different climate states remains unclear."

Line 65: Please briefly explain the physical mechanism by which greenhouse gases induce precipitation increases (e.g., thermodynamics).

Response: As you suggested, we have provided a brief explanation. Please see lines L65-66: "During the rapid industrialization period, the aerosol emissions contributed to a reduction in heavy precipitation over China, partially offsetting the greenhouse gas-induced increase <u>resulting from enhanced atmospheric water vapor holding capacity and transport.</u>"

Lines 57-84: The current literature review on anthropogenic aerosols is overly general. Given that the focus of this study is specifically on sulfate aerosols, I suggest tailoring the literature review to discuss how sulfate aerosols specifically impact regional extreme precipitation, thereby making the transition to your study's focus more natural for readers.

Response: Thank you for this valuable suggestion. We fully agree that the literature review was too general and did not adequately prepare the reader for our study's specific focus on sulfate aerosols. However, because direct studies on sulfate's impacts on extreme precipitation over Asia are limited, we have retained the overview of total aerosol effects, but substantially condensed it. We then sharpened the focus on sulfate by highlighting its dominant role in aerosol loading and ACI effect, thus making the transition to our sulfate-specific focus more natural.

The main revisions are as follows (Lines 77-90): "Among anthropogenic aerosol species, sulfate is of foremost importance in Asian summer monsoon rainfall, where it constitutes the dominant fraction of the regional aerosol burden and exerts strong cooling effects through both ARI and ACI (Liu et al., 2009; Guo et al., 2013; Westervelt et al., 2020; Xie et al., 2022; Fang et al., 2023). Given that sulfate dominates the aerosol loading and the ACI effects, the aforementioned aerosol effects on extreme precipitation are likely largely attributable to sulfate. While its role in mean precipitation is well documented, its impacts on extreme precipitation over Asia have rarely been quantified. Moreover, global warming is expected to alter atmospheric water vapour, static stability, and cloud properties, all of which may influence the efficiency of sulfate-climate interactions. Hence, the sulfate effect on extreme precipitation may differ across climate backgrounds. Yet, whether and how this effect varies under different global warming levels remains unclear, hindering our ability to project future regional climate risks associated with sulfate emission changes."

Line 85: It would be more natural to go to a new paragraph when you introduce what this study will do.

Response: Thank you for the suggestion. Accordingly, we have begun a new paragraph with the sentence on L91 ("In this study, we address…") to clearly separate the introduction of this study's objectives from the preceding background.

Line 97: Please clarify the response of "what" to Asian sulfate aerosol perturbations, e.g., precipitation?

Response: This point has been clarified. Please refer to line 101: "…examines the precipitation responses to Asian sulfate aerosol perturbations…"

Line 100: The heading "methods" is too broad; consider renaming it for better clarity.

Response: As suggested, we have changed the section heading to "Data, Simulations, and Analysis Methods" (formerly "Models, Simulations and Methods").

Lines 138-139: Please provide references or physical justifications for the choice of the 0.75 (σ_{min}) and 300 hPa (p_{min}) thresholds.

Response: Thank you for this comment. We have cited Stjern et al. (2024) as a reference; the relevant text is in Section 2.2. The 300hPa cap prevents thin aerosol layers with spuriously high AOD from being placed in the upper troposphere over mountainous terrain. In practice, this threshold is rarely triggered: most pmin values are around 600 hPa over South Asia and 700 hPa elsewhere (Fig. 1).

Stjern, C., Joshi, M., Wilcox, L., Gollo, A. and Samset, B.: Systematic Regional Aerosol Perturbations (SyRAP) in Asia using the intermediate-resolution global climate model FORTE2, J. Adv. Mod. Earth System, 16, e2023MS004171, 2024.

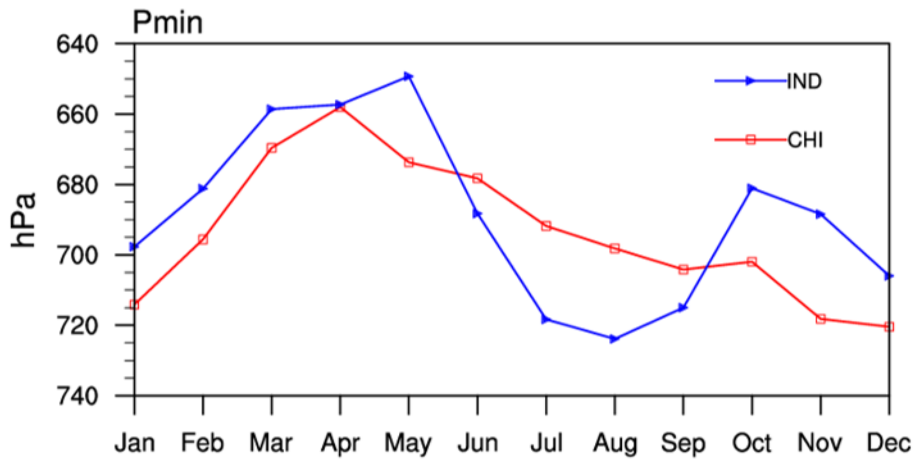

Figure 1. Seasonal evolutions of the regional mean p_{min} for China and India.

Lines 155-156: This sentence is ambiguous. Do you mean that the spin-up period is 200 years, and the last 51 years are selected for analysis? Please clarify.

Response: Apologize for any confusion caused. We have rephrased the relevant statements. Please see lines 159-161: "All simulations were carried out over a total 200-year period, with the first 50 years discarded as spin-up, and the remaining 150 years (model years 51-200) used for the analysis."

Line 163: While you introduced the ACI parameterization, the ARI parameterization scheme is missing. Please provide a brief description of how ARI is implemented.

Response: Thanks for pointing out this omission. We have now added a brief description of the ARI implementation. The added text has been placed before the ACI parameterization paragraph (Lines 169-170): "For ARI, the prescribed SO_4 AOD and vertical profiles are input into the FORTE2 radiation scheme."

Line 185: Please define what "10×" stands for in this context.

Response: We have revised the text accordingly. Please see lines 196-198: "In the perturbation simulations, Asian SO_4 emissions/concentrations are set to ten times their year-2000 levels, while greenhouse gases are fixed at year-2000 levels."

Line 213: Please provide a reference or justification for the 1 mm/day wet-day threshold.

Response: This threshold follows the definition recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI), and has been widely adopted in climate extreme studies. We have added the relevant reference as follows:

Zhang, X., Alexander, L. V., Hegerl, G. C., Jones, P., Klein Tank, A. M. G., Peterson, T. C., Trewin, B., & Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: Climate Change, 2(6), 851–870. doi:10.1002/wcc.147

Lines 241-243: Please state the units for each symbol in the energy budget equations.

Response: Thank you for this suggestion. We have revised the manuscript to explicitly state the units for every symbol in the energy budget equations. Please see lines 253-254: "ω is vertical velocity (Pa s^{-1}), s is DSE (J kg^{-1}), p is pressure (Pa), g is the gravitational acceleration (m s^{-2}), u is horizontal wind vector (m s^{-1})..."

Line 294: Please clarify how the precipitation responses to sulfate aerosols were calculated. For instance, for Fig. 4e, is it the relative difference in PRCPTOT between p1K and SO4_p1K in FORTE2?

Response: Thank you for this comment. We have rephrased the relevant statements in the revised manuscript. Please see lines 161-165: "For the climate response, subtracting each baseline from its corresponding perturbation (e.g., SO_4_p1K-p1K or SO_4_piC-piC) isolates the climate effects of sulfate aerosol relative to a no-aerosol state, including the total (ARI+ACI) effect as well as the separate contributions from ARI and ACI.", and lines 199-201: "The climate response to sulfate aerosols is quantified as the difference between the perturbation and baseline simulations."

Lines 302 & 307: The figure subplot citations appear to be incorrect. In line 302, it likely refers to Fig. 4a, b, e, f, i, j; similarly, please check the subplot numbers cited in line 307 (e.g., Fig. 4c–l).

Response: Thank you for pointing out these mistakes. We have corrected them. Please see line 314: "(Fig. 4a-b, e-f, i-j)" and line 319: "(Fig. 4c-d, g-h, k-l).

Line 308: Please provide statistical evidence to support the claim of "high agreement".

Response: Thank you very much for raising this issue. To provide statistical evidence, we calculated the spatial correlations between the FORTE2 simulations and the PDRMIP MMM for the four precipitation indices. The coefficients are relatively low (e.g., ~0.5 for PRCPTOT, and 0.3~0.5 for the other three indices). This outcome is not unexpected, given that the sulfate forcing in PDRMIP is roughly one order of magnitude larger than in FORTE2 experiments, and the two models differ substantially in complexity and parameterizations. Hence, we have revised the wording to avoid overstating the agreement. Rather than claiming "high agreement", we now emphasize the qualitative consistency in the sign and regional distribution of the dominant responses. The revised sentence (lines 320-322): "While FORTE2 is a model of lower complexity, it broadly reproduces the key regional sign patterns of the five PDRMIP models, particularly drying over East Asia and South Asia and wetting over northwestern India."

Lines 389-401: Section 3.3 focuses on the differences between the two climate scenarios. Therefore, the analysis (e.g., "Relative to SO4_piC, SO4_p1K exhibits weaker cold anomalies over northern India…") should be the primary focus of this paragraph, and the detailed description of SO4_piC for Fig. 10a–d can be toned down.

Additionally, it would be clearer to directly show the difference between SO4_piC and SO4_p1K for the variables in Fig. 10, moving the previous Fig. 10a–h to the supplement.

Response: Thank you for this insightful suggestion. We have reduced the emphasis on the detailed description of the SO4_piC response and restructured the paragraph to better highlight the contrast between SO4_p1K and SO4_piC. The revised text now reads (lines 403-412): "In SO_4_piC, the enhanced δH_{Th_h} over northern India is associated with the north–south surface temperature gradient, featuring warm anomalies over southern India and cold anomalies over northern India (Fig. 6h). Relative to the response in SO_4_piC, the response in SO_4_p1K exhibits significant warm anomalies over northern India (Fig. 10a), corresponding to the weaker north–south surface temperature gradient and δH_{Th_h} in SO_4_p1K (Fig. 6h and 9b). These warm anomalies are driven by increased surface SW, which results from diminished convective cloud cover and stronger descent over northwestern India (Fig. 10b-d), indicating a dampened local meridional circulation in SO_4_p1K (Fig. 6b and c). This attenuation results from the increased lower troposphere stability in p1K compared to that in piC (Fig. 10e)."

As suggested, we have replaced the original Fig. 10a–h with a new figure that directly presents the difference fields [(SO4_p1K-p1K) minus (SO4_piC-piC)] for the key variables. The figure caption and relevant in-text references have been updated accordingly. The original individual response panels can be seen in Figure 6.

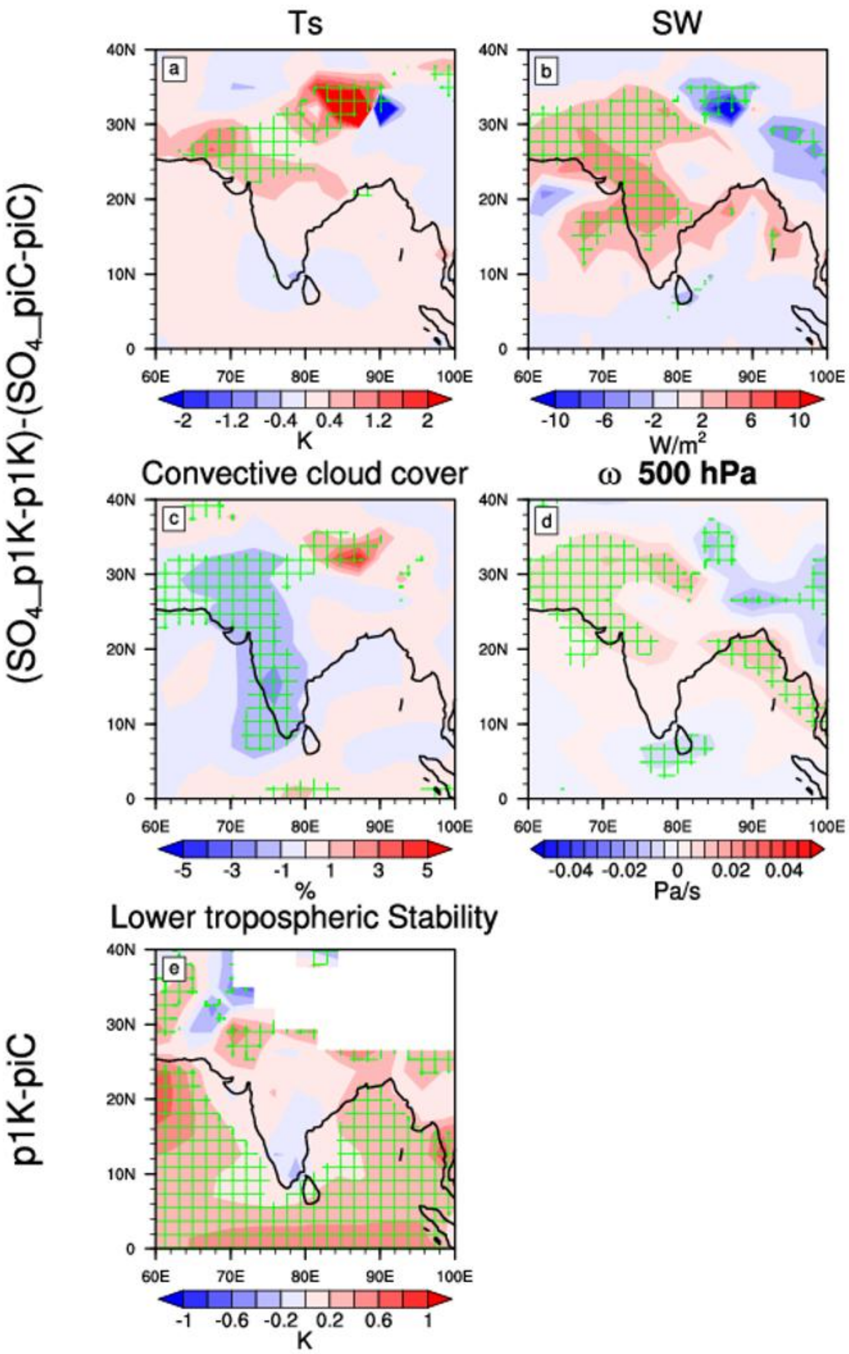

Figure 10. Summer spatial patterns of the difference in the responses to Asian SO_4 aerosol forcing between the p1K and piC climate states, defined as (SO_4_p1K-p1K) - (SO_4_piC-piC): (a) Ts (K), (b) net surface SW (W m^{-2}), (c) convective cloud cover (%), and (d) ω at 500 hPa (Pa s^{-1}). (e) Differences in lower tropospheric stability (θ_{850}-θ_{sfc}, where θ is potential temperature; K) between p1K and piC (p1K- piC). Green grid lines indicate regions where the responses are statistically significant above the 90% confidence level based on a two-tailed Student's t-test.

Line 403: Does "response" denote the difference between the aerosol-added experiment and the baseline scenario (e.g., (ARI_p1K - p1K) / p1K for PRCPTOT)? If so, please explicitly define this in the figure caption, and clarify the sub-panel titles (e.g., using "ARI_p1K" directly can be misleading).

Response: We sincerely appreciate the suggestion. Following your recommendation, we have revised the caption to explicitly define the term "response" and its calculation method right at the beginning. Regarding the sub-panel titles, we have retained the original notation (e.g., "ARI_p1K"). This choice follows the established convention throughout our manuscript, where the name of an aerosol-forced experiment is routinely used to denote its corresponding response relative to the baseline (e.g., "SO4_p1K" in other figures). Given that the definition of "response" is now unambiguously stated in the caption, we believe that using the experiment names for the sub-panels no longer causes any confusion and maintains stylistic consistency across all figures.

The new caption now reads: "Spatial patterns of summer responses in (a, b, g, h) PRCPTOT and (d, e, j, k) R95p (%) to Asian SO_4 aerosol forcing [e.g., (ARI_p1K – p1K)/p1K, expressed as a percentage], and (c, f, i, l) the difference in these responses between the p1K and piC climate states [e.g., (ARI_p1K-p1K)/p1K-(ARI_piC-piC)/piC]. (a, d) ARI_p1K; (b, e) ARI_piC; (c, f) difference between (ARI_p1K-p1K)/p1K and (ARI_piC-piC)/piC. (g, j) ACI_p1K; (h, k) ACI_piC; (i, l) difference between (ACI_p1K-p1K)/p1K and (ACI_piC-piC)/piC."

Lines 414-425: Figs. 11c, f, i, l and Fig. 12, along with the corresponding text, actually focus on the differences between the two climate conditions. This material should either be restructured into Section 3.3 or streamlined.

Response: We sincerely appreciate this helpful suggestion. In the revised manuscript, we have restructured the relevant material into a new subsection (3.3.2 "The respective roles of ARI and ACI effects and linearity") within Section 3.3 ("Differences between the p1K and piC climate conditions and their potential causes").

Line 437: Please specify what kind of "moisture" is being referred to (water vapor?).

Response: We have replaced the term "moisture" with "water vapor" in the text. Please see line 448.

Line 449: Replace "adding" with "the additional"

Response: We have revised this accordingly. Please refer to line 487.

Line 453: Since precipitation is also evaluated in Section 3.1, it should be mentioned briefly here as well.

Response: Thank you for this observation. In the revised manuscript, we have added a short sentence referring back to the precipitation changes discussed in Section 3.1 (lines 492-493): "The model evaluation shows that both the PDRMIP models and FORTE2 reasonably reproduce the observed precipitation patterns and atmospheric circulation."

Line 469 The discussion regarding resolution issues does not seem well-integrated here; consider moving it to the Discussion section.

Response: Thank you for this suggestion. In the revised manuscript, we have moved this part to the Discussion section. The revised text now reads: "The energy budget analysis shows that the dynamic vertical advection (δH_{Dy_v}) is the dominant contributor to precipitation suppression over East and South Asia in most models examined here. Nevertheless, inter-model differences do exist, as exemplified by the NorESM1 model, in which the transient term (δH_{trans}) exerts the strongest influence over East Asia, while changes in horizontal winds (δH_{Dy_h}) are the leading factor over South Asia (Fig. 5). Hence, future work should further investigate the reasons for this model diversity, particularly by disentangling the roles of model resolution, physics parameterizations, and their interactions with aerosol processes, to refine our understanding of the mechanisms governing aerosol-induced precipitation changes."

Line 447: The Conclusion should be more concise and compact, while outlining clear directions for future research. Currently, it largely repeats the results without offering future perspectives. Please sharpen the summary and add forward-looking statements stemming from your findings.

Response: We sincerely thank you for this constructive suggestion. In the revised manuscript, we have sharpened the Conclusion, and added forward-looking statements that follow directly from our findings. These include scenario simulations with prescribed aerosol trends and varying background warming to test the linearity assumption, and process-level studies to identify the thresholds governing the ARI–ACI regime shift.

The revised text now reads: “In this study, we have examined the responses of Asian summer mean and extreme precipitation to the additional Asian sulfate aerosols, and investigated the differences in these responses between the pre-industrial +1K (p1K) and pre-industrial (piC) climate conditions and the associated physical mechanisms, using both the SyRAP simulations based on FORTE2 and PDRMIP multi-model simulations. Our main findings are as follows.

The model evaluation shows that both the PDRMIP models and FORTE2 reasonably reproduce the observed precipitation patterns and atmospheric circulation. Increased Asian sulfate forcing significantly reduces the frequency and intensity of summer extreme precipitation over East Asia and South Asia, with R95p exhibiting heightened sensitivity relative to mean precipitation. The energy budget analysis reveals that these reductions are driven predominantly by the dynamic vertical advection, reflecting anomalous descent induced by surface cooling via ARI and ACI effects. FORTE2 is qualitatively consistent with the PDRMIP models in the sign, regional distribution, and the physical mechanism of the dominant precipitation responses.

Under the same Asian sulfate AOD forcing, the precipitation suppression over northern India is significantly stronger under p1K conditions than under piC. This difference stems from a weakened north–south temperature gradient due to increased lower-tropospheric stability in the p1K state, which reduces the counteracting effect of horizontal thermal advection on the vertical dynamical suppression, thereby allowing the dynamical suppression to dominate more effectively. Additionally, the ACI effect consistently suppresses Indian precipitation, but this suppression weakens under the warmer, wetter p1K climate. Critically, ARI and ACI combine linearly under piC but nonlinearly under p1K, indicating a regime shift in their interaction that reverses the sign of the climate-state difference when the effects are summed versus combined.

These findings indicate that under global warming, the background climate amplifies suppression of precipitation, including extreme events, by Asian sulfate aerosols over northern India through its influence on atmospheric stability and circulation strength. This amplification is independent of changes in the aerosol burden itself. Yet current assessments tend to attribute aerosol-induced precipitation changes primarily to emission differences, overlooking the modulating role of the mean-state climate itself. If this modulating effect also holds for sulfate aerosol reductions and is approximately linear, northern India is likely to experience more severe extreme precipitation events in the future, because ongoing aerosol emission reductions directly enhance precipitation, and continued global warming both intensifies precipitation directly and amplifies the precipitation increase driven by aerosol reductions.

However, this linearity assumption remains untested. Dedicated scenario simulations that combine prescribed aerosol trends with different levels of background warming are needed to verify it and quantify the associated risk. In addition, the transition from linear to nonlinear ARI–ACI interaction under a warmer climate calls for targeted process-level studies to identify the microphysical and dynamical thresholds governing this regime shift."

Line 492: The Discussion section should appear before the Conclusion. Also, note that the Introduction states Section 4 provides a summary and discussion, but Section 5 is labeled as Discussion. Please ensure consistency.

Response: We sincerely thank you for pointing out this inconsistency. In the revised manuscript, we have corrected the order so that the Discussion section now appears before the Conclusion. The Discussion is now Section 4, and the Conclusion is Section 5. Accordingly, we have revised the statement in the Introduction to accurately reflect this structure, changing "Sections 4 and 5 provide a discussion and conclusion".