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The revised manuscript entitled "Distinct drivers of recent seasonal precipitation increase over Central Asia: roles of anthropogenic aerosols and greenhouse gases" by Jianing Guo, Xiaoning Xie, Gunnar Myhre, Drew Shindell, Alf Kirkevåg, Trond Iversen, Apostolos Voulgarakis, Toshihiko Takemura, Ke Shang, Xinzhou Li, Zhengguo Shi, Yangang Liu, Xiaodong Liu, Hong Yan

We thank the ACP Handling Editor for their hard work and the three anonymous referees for their constructive comments, which have significantly improved our manuscript. We greatly appreciate the positive and helpful comments from all reviewers (Reviewer #1, Reviewer #2, and Reviewer #3) and have addressed the reviewers' concerns in the point-by-point responses provided below (reviewers comments' in black and our responses in blue). We have uploaded the file entitled "Response to reviewers.pdf".

Best wishes,
Xiaoning Xie

Response to Reviewer #1:

This manuscript investigates the drivers of recent seasonal precipitation increases over Central Asia, focusing on differences between winter and summer. By combining PDRMIP idealised single-forcing experiments with CMIP6 historical and future simulations, the authors argue that greenhouse gases dominate winter precipitation increases via thermodynamic moisture enhancement, while anthropogenic aerosols, especially Asian sulfate, dominate summer wetting through circulation adjustments.

The topic is relevant to ACP as it sits at the interface of aerosol forcing, circulation dynamics, and hydroclimate change. The manuscript is generally well written, clearly structured, and supported by a substantial body of previous literature. The use of PDRMIP sensitivity experiments is appropriate and it is useful to isolate mechanisms, while the link to CMIP6 past and future experiments improve the context and perspectives.

However, several conceptual and methodological limitations weaken the conclusions. I recommend acceptance after satisfactorily addressing these comments.

Response: Thank you very much for the constructive comments, which have significantly improved our manuscript. According to the reviewer's comments, we have made several major revisions including the time period (1979–2014) used to diagnose and attribute seasonal precipitation changes over Central Asia, the relative importance of internal variability, and different GCMs in PDRMIP and DAMIP by addressing the conceptual and methodological issues and strengthening the conclusions.

(1), In our manuscript, we focus on the time period from 1979 to 2014 to diagnose and attribute seasonal precipitation changes over Central Asia. To clearly claim this point, we have added a new Figure S13 in Supporting Information to show the time series of regionally averaged precipitation over Central Asia derived from the GPCP (1979–2025), CRU (1950–2024), and GPCC (1950–2019). The linear trends of the the ensemble mean of the three observational datasets indicate an increase in precipitation over Central Asia during 1979–2014 (Supplement Figs. 13). In comparison with 1950–2014 period (0.12 mm day^{-1} per 100 years), it has a larger increasing trend in summer precipitation during 1979–2014 (0.26 mm day^{-1} per 100 years). During this period, anthropogenic aerosol emissions in Asia increased substantially (Ohara et al., 2007; Lu et al., 2011). Since the early 2010s, anthropogenic aerosol optical depth (AOD) in East Asia has decreased markedly due to China's clean air actions and climate policies (Zheng et al., 2018; Samset et al., 2019). It shows a decreasing trend in summer precipitation over Central Asia with -0.16 mm day^{-1} per 100 years, likely due to the effects induced by anthropogenic aerosol reduction. Based on these changes in precipitation trends and the corresponding anthropogenic aerosol emission background, we selected 1979–2014 as the research period.

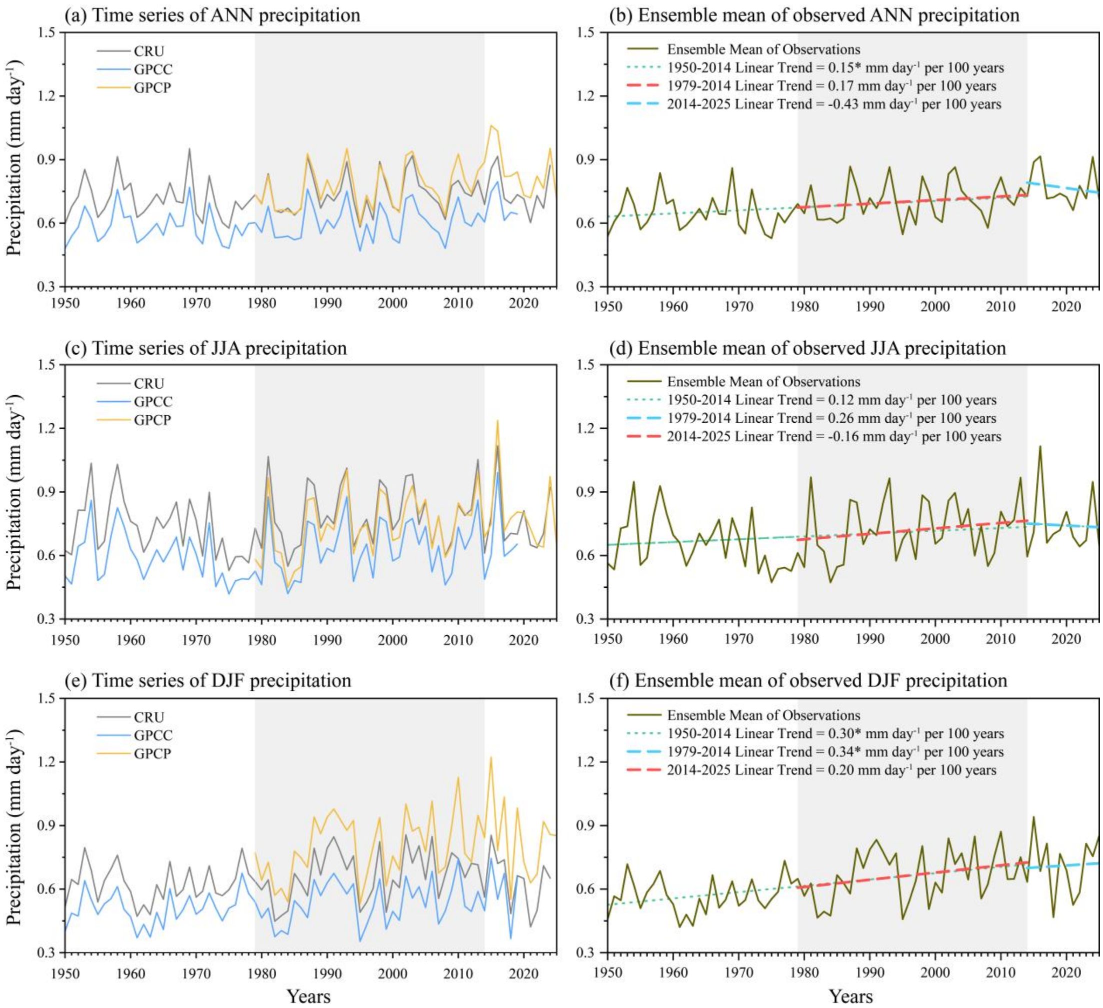

Figure S13. Time series of precipitation over Central Asia derived from GPCP (1979–2025), CRU (1950–2024), and GPCC (1950–2019). (a) Annual precipitation time series from the three observational datasets. (b) Annual precipitation time series of the ensemble mean of the three datasets. (c, d) Same as (a, b), but for winter precipitation. (e, f) Same as (a, b), but for summer precipitation. The dashed lines represent the liner trend in precipitation (mm day^{-1} per 100 years).

(2), We agree that internal variability can exert a substantial influence on regional precipitation changes. To further examine the influence of internal variability on precipitation trends over Central Asia, we analyze three CMIP6 large-ensemble models, including ACCESS-ESM1-5 (40 members), CanESM5 (40 members), and

MIROC6 (50 members). The externally forced signal is calculated from the mean of all ensemble members, and internal variability is calculated from the deviation of each ensemble member from the ensemble mean (Wu et al., 2021). Supplement Fig. S12 shows substantial differences in precipitation trends attributable to internal variability among the three models, suggesting that internal variability has a non-negligible impact on the estimated winter and summer precipitation variations during 1979–2014. Additionally, it shows that the CMIP6 historical simulations do capture positive seasonal precipitation trends over Central Asia in Figure 6. However, the increasing precipitation trends are underestimated (particularly for summer). The positive historical summer precipitation trend is underestimated by about 37% relative to the observations. It suggests that the underestimation of the multi-modal mean probably derives from the limitation of the models in capturing internal variability, such as the tropical Pacific decadal variability and the Atlantic multidecadal variability (Jiang et al., 2021; Yao et al., 2025). Our results suggest that, in addition to internal variability, greenhouse gases (GHGs) and anthropogenic aerosols are important external forcings for the recent increase in precipitation over Central Asia in Supplement Figure S12.

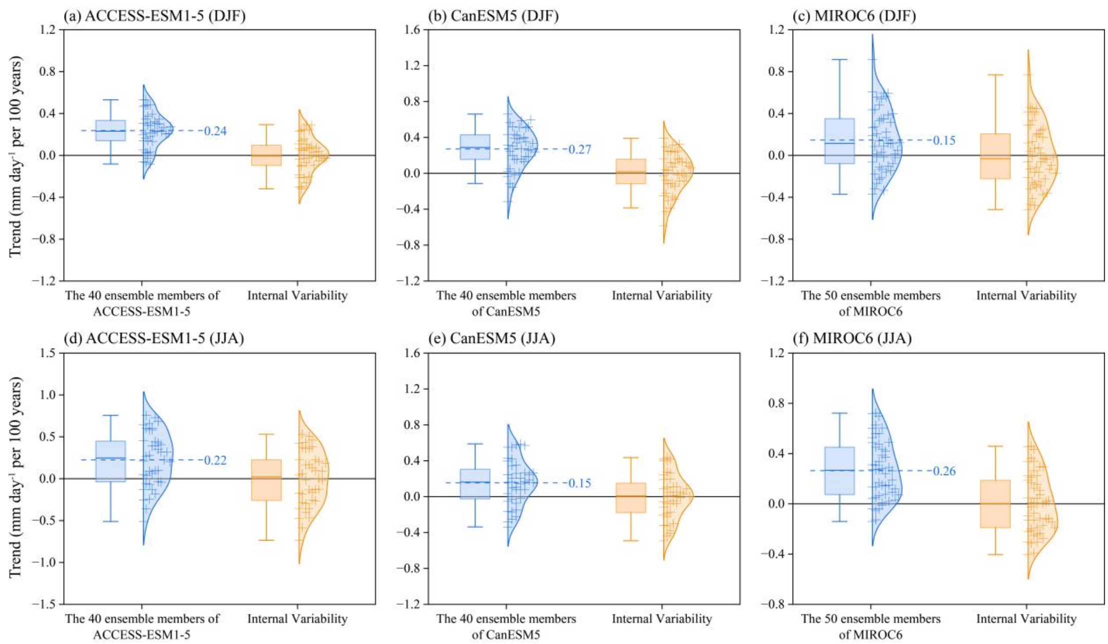

Figure S12. Linear trends (mm day^{-1} per 100 years) of precipitation during 1979–2014 from large ensembles of ACCESS-ESM1-5 (40 members), CanESM5 (40 members), and MIROC6 (50 members). (a–c) DJF precipitation trends. (d–f) JJA precipitation trends. The numbers and the dotted lines indicate the ensemble mean of the precipitation trends. Boxes indicate the 25th, 50th, and 75th percentiles and the whiskers indicate the minimum and maximum values. Plus signs represent the trends in regionally averaged precipitation from individual ensemble members, and curves show kernel density estimates of the trend distribution, with the bandwidth selected using Scott's rule.

(3), We use multi-model simulations in PDRMIP to investigate the impacts of different individual external forcings on winter and summer precipitation over Central Asia and to examine the associated physical mechanisms. We further analyze the attribution of external forcings during the historical period and possible future changes using DAMIP and ScenarioMIP in CMIP6. In the PDRMIP analysis, nine models are available. Among them, CanESM2 and HadGEM2 did not perform regional aerosol experiments, and NCAR-CESM1-CAM4 lacks most of the variables required for this study in the BCx10Asia experiment. When calculating the differences between each forcing experiment and the base experiment, we include all available models with complete data. In the DAMIP historical attribution analysis, we use 18 models previously downloaded in earlier studies to analyze historical precipitation trends. Following the reviewer's suggestion, we additionally provide spatial distributions of precipitation trends using 12 models. As shown in Figure R1, the main conclusions are similar despite differences in the number of models. Therefore, we retain the original results based on a larger model ensemble with 18 models.

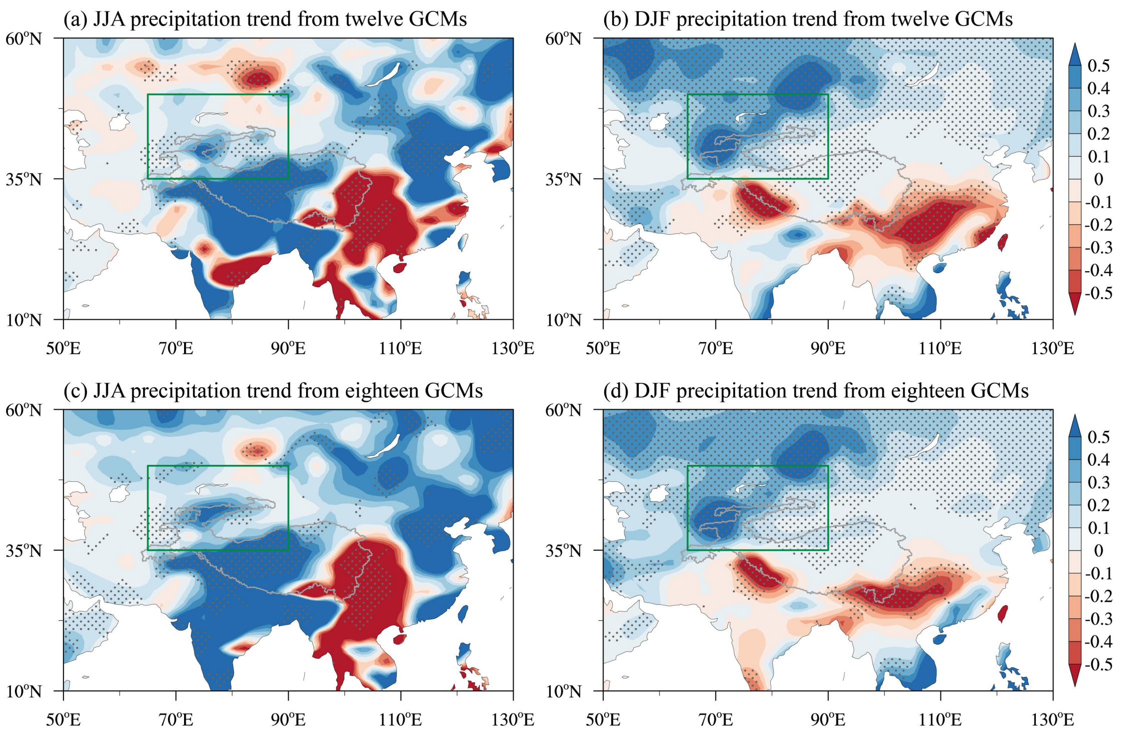

Figure R1. Spatial distribution of precipitation trends over Central Asia from DAMIP historical simulations using different numbers of models. (a) Winter and (b) summer precipitation trends (mm day^{-1} per 100 years) based on 12 models. (c, d) Same as (a, b), but based on 18 models. Thick green boxes delineate the region of Central Asia. The thick gray curves denote Tibetan Plateau terrain height > 2500 m. The gray stippled regions indicate where at least 70% of the models agree on the sign of the trend.

1. The Interpretation of PDRMIP aerosol perturbations and relevance to real world trends is somewhat overstated. The PDRMIP experiments are intentionally idealised, but the manuscript at times over-interprets these sensitivity experiments as direct analogues of historical forcing and what shown in Fig 1 in terms of observational changes. For example, the relative importance of sulfate versus BC in recent decades depends strongly on regional emission trends, which have evolved non-uniformly (e.g., post-2010 reductions over China and increases over South Asia). Although the authors acknowledge these limitations briefly in the discussion, the main text and

conclusions should be more explicit that PDRMIP results indicate sensitivities rather than quantitative attribution, and that the inferred role of aerosol forcing does not imply a one-to-one explanation of the observed trend. Along these lines, I wonder whether the authors should first show the analysis of CMIP historical experiments, and then use PDRMIP to corroborate the CMIP6 results.

Response: We thank the reviewer for this constructive comment. We fully agree with the point about the idealized single-forcing sensitivity experiments in the PDRMIP. We used the PDRMIP sensitivity experiments to illustrate a relationship between different external forcings and the Central Asian precipitation changes in different seasons, primarily used to understand underlying mechanisms. To further conduct quantitative attribution of regional precipitation changes and compare with observations, we analyze the relative contributions of different external drivers to the winter and summer precipitation increase using DAMIP simulations in CMIP6. DAMIP multi-model ensemble results indicate the recent increases in winter and summer precipitation over Central Asia and obvious seasonal differences in precipitation drivers in Figure 6, which support the results of idealized sensitivity experiments in PDRMIP. Therefore, we have revised the relevant descriptions in the main text and conclusions to clarify that the PDRMIP results reflect mechanistic sensitivity rather than a direct explanation of the observed trends, and we have compared the DAMIP results with observations.

2. I am also wondering: other regions, Europe in particular, may also play a role. I suggest the authors to consider also the 5x global sulfate experiment, and possibly also the European emissions only.

Response: Thank you for the comment. As suggested, we examine the winter and summer precipitation changes under a tenfold increase in European sulfate concentrations (Sulx10Eur) and a fivefold increase in global sulfate concentrations (Sulx5) as shown in Figure R2. Under Sulx10Eur forcing, it shows insignificant changes in winter and summer precipitation over Central Asia. Under Sulx5 forcing, winter precipitation decreases significantly across most of Central Asia, which may be associated with reduced oceanic moisture transport (Yao et al., 2025). In summer, precipitation increases over parts of the region, which may be partly attributable to the influence of Asian sulfate aerosols.

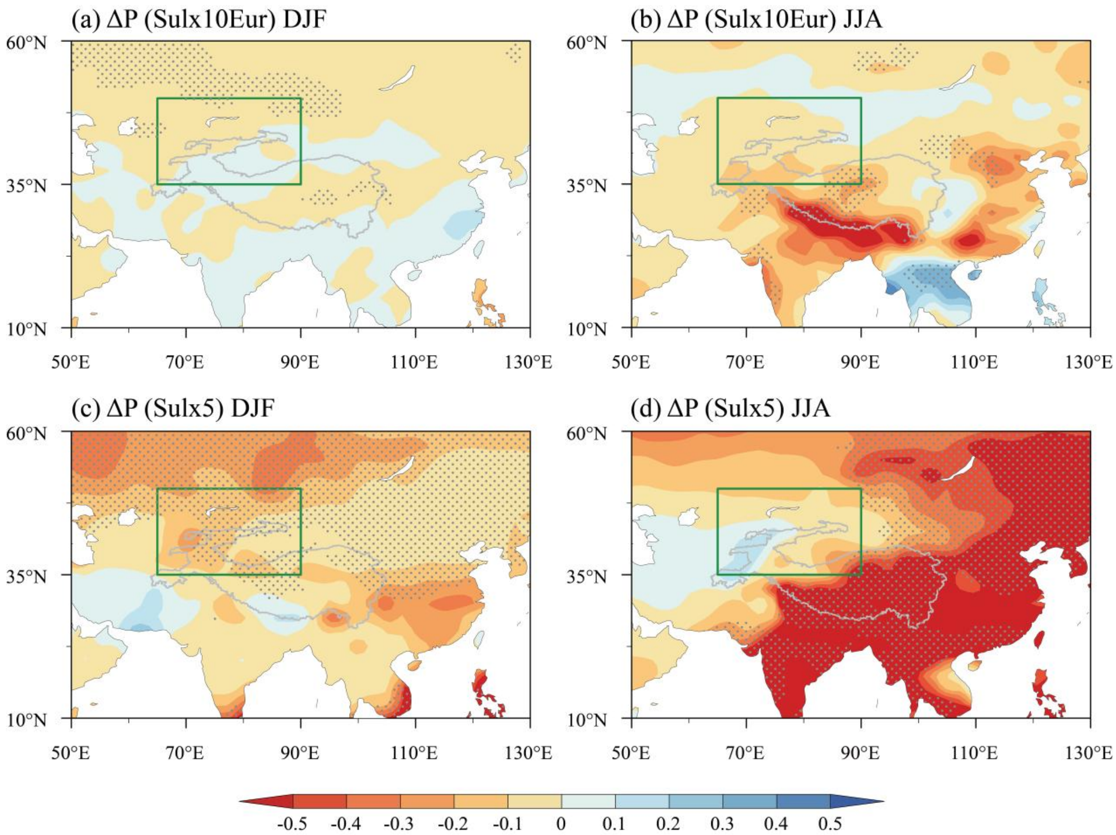

Figure R2. Spatial distributions of multi-model mean precipitation responses to Sulx10Eur and Sulx5 forcings in PDRMIP. Multi-model mean precipitation changes (mm day^{-1}) under Sulx10Eur in (a) DJF and (b) JJA, and under Sulx5 in (c) DJF and (d) JJA. The region of Central Asia is delineated by thick green boxes. Thick gray curves denote Tibetan Plateau terrain height > 2500 m. Gray stippling indicates regions where the PDRMIP multi-model mean changes exceed 1 inter-model standard deviation from zero.

3. The manuscript attributes much of the observed precipitation increase to anthropogenic forcing, supported by DAMIP hist-aer simulations. However, studies examining for example broad-scale Asian precipitation changes have shown that it is strongly influenced by internal variability (e.g., Atlantic multidecadal variability). In this regard, the relatively short period (1979–2014) poses some challenges to separate forced signals from low-frequency internal variability, and thus to attribute observed

trends with marked certainty. Also, CMIP6 multi-model means are known to underestimate internal variability, which the authors note, but the implications are not fully explored. Finally, no explicit attempt is made to quantify how much of the observed trend could plausibly arise from internal variability alone.

Response: Thanks for your comments. We agree that internal variability can exert a substantial influence on regional precipitation changes. To further examine the influence of internal variability on precipitation trends over Central Asia, we analyze three CMIP6 large-ensemble models, including ACCESS-ESM1-5 (40 members), CanESM5 (40 members), and MIROC6 (50 members). The externally forced signal is calculated from the mean of all ensemble members, and internal variability is calculated from the deviation of each ensemble member from the ensemble mean (Wu et al., 2021). Supplement Fig. S12 shows substantial differences in precipitation trends attributable to internal variability among the three models, suggesting that internal variability has a non-negligible impact on the estimated winter and summer precipitation variations during 1979–2014. Additionally, it shows that the CMIP6 historical simulations do capture positive seasonal precipitation trends over Central Asia in Figure 6. However, the increasing precipitation trends are underestimated (particularly for summer). The positive historical summer precipitation trend is underestimated by about 37% relative to the observations. It suggests that the underestimation of the multi-modal mean probably derives from the limitation of the models in capturing internal variability, such as the tropical Pacific decadal variability and the Atlantic multidecadal variability (Jiang et al., 2021; Yao et al., 2025). Our results suggest that, in addition to internal variability, greenhouse gases (GHGs) and anthropogenic aerosols are important external forcings for the recent increase in precipitation over Central Asia in Supplement Figure S12.

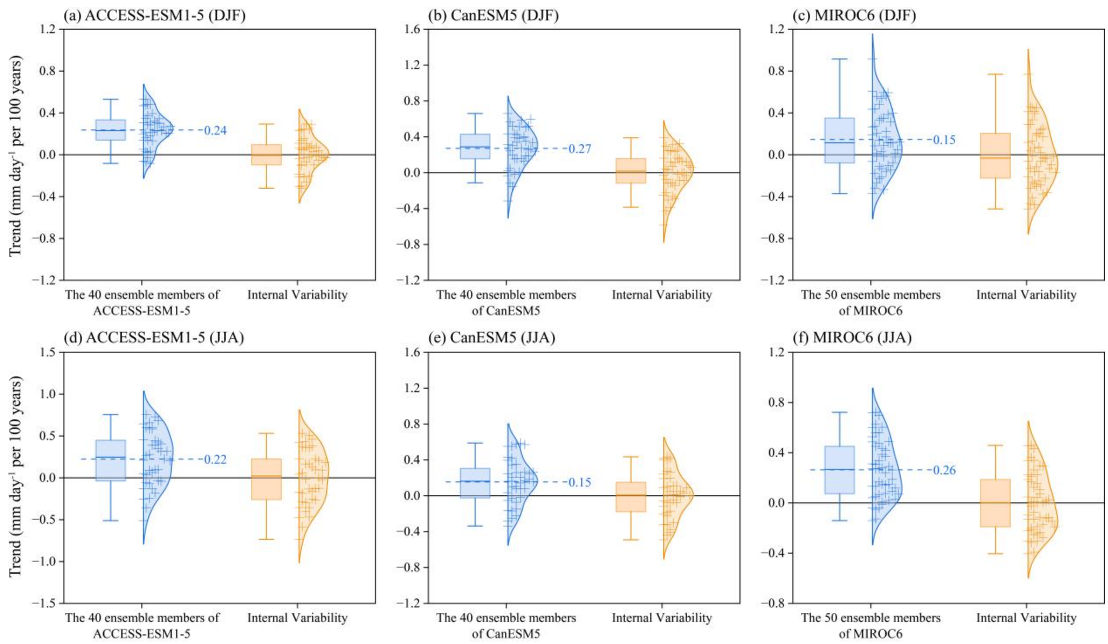

Figure S12. Linear trends (mm day^{-1} per 100 years) of precipitation during 1979–2014 from large ensembles of ACCESS-ESM1-5 (40 members), CanESM5 (40 members), and MIROC6 (50 members). (a–c) DJF precipitation trends. (d–f) JJA precipitation trends. The numbers and the dotted lines indicate the ensemble mean of the precipitation trends. Boxes indicate the 25th, 50th, and 75th percentiles and the whiskers indicate the minimum and maximum values. Plus signs represent the trends in regionally averaged precipitation from individual ensemble members, and curves show kernel density estimates of the trend distribution, with the bandwidth selected using Scott's rule.

4. The proposed circulation mechanisms—southward or northward shifts of the westerly jet and associated changes in moisture transport—are physically plausible. However, in several places the manuscript relies on qualitative inference rather than quantitative diagnosis. For example, moisture transport pathways (e.g., from the Atlantic versus Indian Ocean) are discussed, but moisture budget or convergence are not presented.

Response: Thanks for your comments. We have added the figures about the convergence/divergence of the vertically integrated moisture flux induced by Sulx10Asia and BCx10Asia forcings (Supplement Fig. S10). Under Sulx10Asia, enhanced moisture transport from the Atlantic and Indian Ocean to Central Asia and increased moisture flux convergence increase the summer precipitation over Central Asia. In contrast, BCx10Asia suppresses moisture transport from the Atlantic into Central Asia and reduces regional moisture flux convergence, leading to decreased summer precipitation. We have revised the corresponding descriptions in Section 3.2.

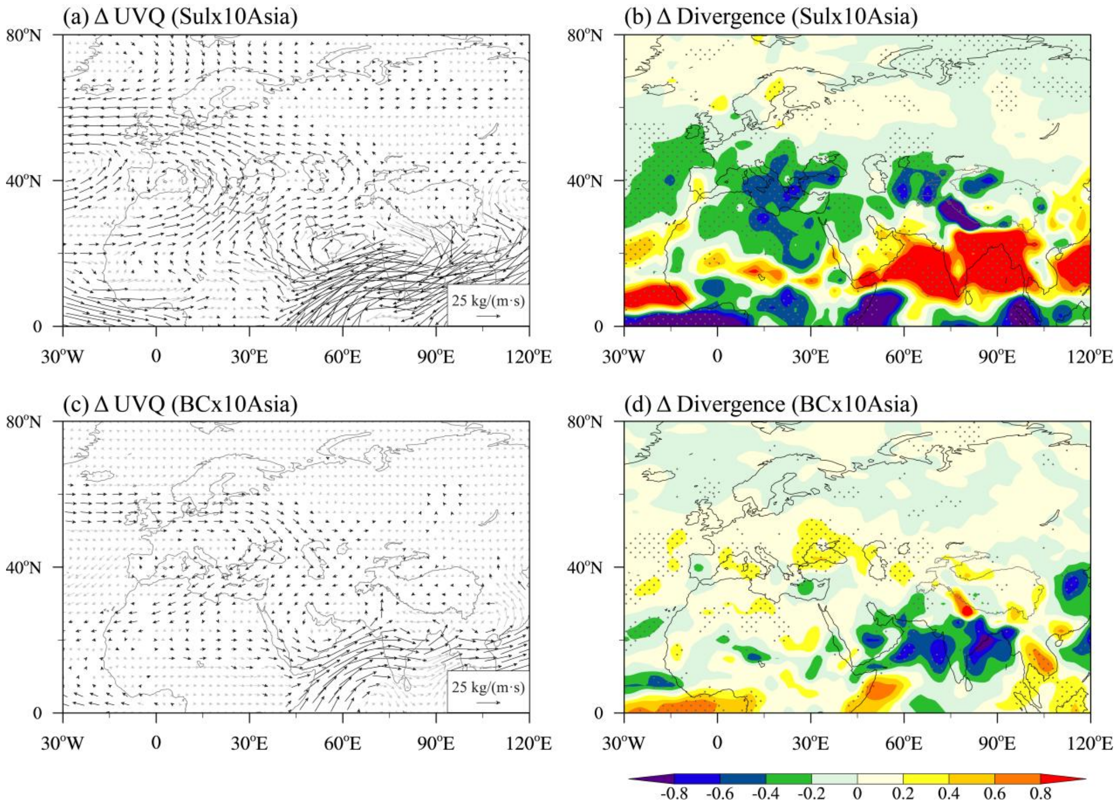

Figure S10. Multi-model mean JJA anomalies induced by Sulx10Asia and BCx10Asia forcings in PDRMIP. (a) Changes in vertically integrated (surface–300 hPa) moisture flux (Δ UVQ, kg m^{-1} s^{-1}) and (b) moisture divergence (Δ Divergence 10^{-5} kg m^{-2} s^{-1}) under Sulx10Asia forcing. (c, d) Same as (a, b), but for BCx10Asia forcing. Black arrows in (b, d) and gray stippled regions in (a, c) indicate where the PDRMIP multi-model mean changes exceed 1 standard deviation from zero.

5. The winter precipitation increase is attributed almost entirely to thermodynamic moisture enhancement under global-scale forcing. While this is reasonable, the analysis risks being overly simplistic and based on limited diagnostics.

Response: Thanks for your comments. Previous studies indicate that global warming leads to increased atmospheric water vapor with increasing temperature, which can affect precipitation (Allen and Ingram, 2002; Held and Soden, 2006). In addition, the increase in winter precipitation under global warming over mid-latitude regions is dominated by thermodynamic effects associated with increased atmospheric moisture (Seager et al., 2010; Xue et al., 2022). Our results show that global-scale forcings lead to tropospheric warming and intensify supplies of atmospheric water vapor, which results in statistically significant increases in water vapor in Figure 4. Meanwhile, the low-level tropospheric circulation responses are relatively weak in Figure 4. Therefore, thermodynamic processes are mainly associated with the enhanced winter precipitation in Central Asia under global-scale forcing. We have added the above references in the revised manuscript.

6. The projected decline in summer precipitation under SSP scenarios is attributed primarily to reductions in Asian aerosol emissions. While this is plausible, it rests on assumptions that deserve clearer qualification and is somewhat speculative. SSP aerosol trajectories are known to underestimate recent emission reductions in China and may not capture future policy shifts accurately. Also, the relationship between aerosol reductions and circulation changes, concurrently with GHG changes, may be nonlinear. In view of this and similar considerations, it is hard to support the dominant role of aerosol changes in driving future precipitation variations.

Response: We thank the reviewer for this important comment. Based on the sensitivity experiments from PDRMIP, our results indicate that Asian sulfate aerosols play an important role in the increase of summer precipitation over Central Asia, which is also supported by the historical attribution analysis using DAMIP. Under future SSP scenarios, the analysis of precipitation trends during 2015–2100 suggests that reductions in Asian aerosol emissions may help explain the projected decrease in summer precipitation across most regions of Central Asia. We absolutely agree with the reviewer's point that SSP aerosol trajectories may not capture future policy shifts accurately. Thus, we lower our point about the precipitation changes under future scenarios in CMIP6. Recently, a more realistic scenario of SSP2-com from the Chinese Academy of Meteorological Sciences has been provided, derived from China's net-zero pathway (Zhong et al., 2025). We will conduct new ScenarioMIP simulations based on this scenario to improve our prediction/projection of regional climate.

We agree with the reviewer's concerns about the potential nonlinearity in the combined effects of aerosols and greenhouse gases on future precipitation changes. We have added the corresponding descriptions in Section 4 as "*This study is mainly based on the PDRMIP and DAMIP single-forcing sensitivity experiments to assess the historical precipitation changes in Central Asia, which makes it difficult to capture the potential impact of nonlinearity among different forcings on regional precipitation. Previous studies have shown that the nonlinear effects between* CO_2 *and anthropogenic aerosols can significantly influence the regional seasonal precipitation (Deng et al., 2020; Herbert et al., 2021). Further work is needed to assess how nonlinear effects impact seasonal precipitation in Central Asia.*"

7. The observational analysis would be much stronger if it were to incorporate a few other observational datasets (perhaps station-based) as well as some dynamical analyses, for example, based on ERA5.

Response: Thanks for your comments. As suggested, we have added the additional station-based precipitation datasets, including the Global Precipitation Climatology Center (GPCC) and the Climatic Research Unit (CRU), and show the spatial distributions of precipitation trends over 1979–2014 in Supplement Fig. S2. The spatial distributions of annual, winter, and summer precipitation trends derived from GPCC and CRU show positive precipitation trends over Central Asia. In addition, we examine the changes in the Central Asian summer westerly jet based on ERA5 zonal wind trends at 200 hPa for 1979–2014 and 2014–2025 (Supplement Fig. S3). The southward shift of the westerly jet is closely associated with the summer wetting trend over Central Asia (Peng and Zhou, 2017; Peng et al., 2018), and the northward shift will decrease summer precipitation (Zhao et al., 2014). During 1979–2014, the

Central Asian westerly jet exhibited a southward shift, coinciding with a significant increase in anthropogenic aerosol emissions in Asia. This observed tendency is similar to the circulation response to Asian sulfate aerosol forcing in the sensitivity experiments. Since the early 2010s, the westerly jet has tended to shift northward, which may be related to decreasing aerosol emissions associated with China's clean air actions and climate policies.

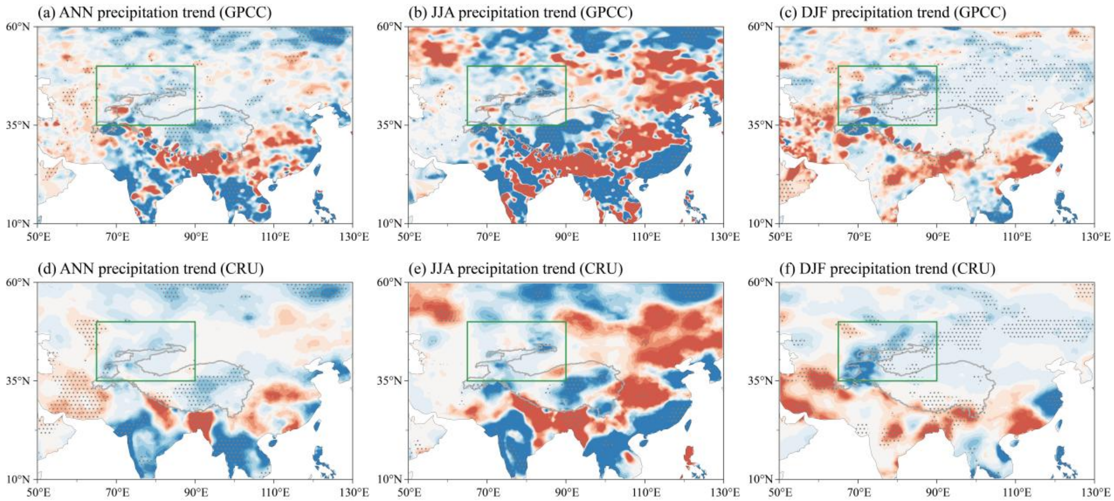

Figure S2. Spatial distributions of precipitation trends over Central Asia. (a) Annual (January–December, ANN), (b) summer (June–August, JJA), and (c) winter (December–February, DJF) precipitation trends (mm day^{-1} per 100 years) derived from GPCC during 1979–2014. (d–f) Same as (a–c), but derived from CRU. The region of Central Asia (35°N–50°N, 65°E–90°E) is delineated by thick green boxes. The stippling indicates trends that are statistically significant at the 90% confidence level based on a standard *t*-test. The thick gray curves denote Tibetan Plateau terrain height > 2500 m.

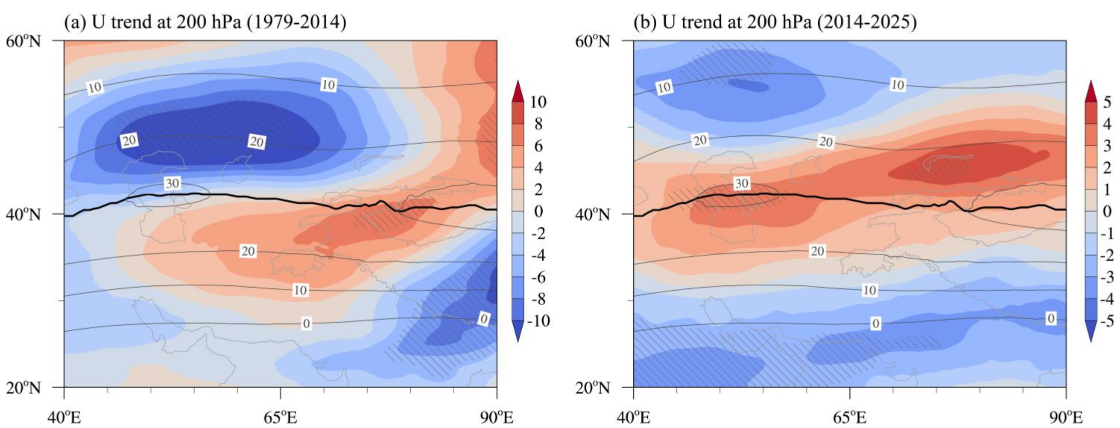

Figure S3. Spatial distributions of JJA zonal wind trends. (a) 1979–2014 (m s^{-1} per 100 years). (b) 2014–2025 (m s^{-1} per decade). The dark gray curves represent the climatological zonal wind and the thick black line denotes the westerly jet axis for 1979–2014. The slanted lines indicate trends that are statistically significant at the 90% confidence level based on a standard *t*-test.

8. When comparing models across different experiments, the authors make use of different model ensembles across experiments. A recurring methodological issue in the manuscript is the use of different sets and numbers of models for different components of the analysis, including PDRMIP sensitivity experiments, CMIP6 historical simulations, DAMIP single-forcing runs, and future SSP projections. For example, differences between aerosol- and GHG-driven responses may partly reflect differences in model composition, not just differences in forcing. While the models used in PDRMIP are necessarily different from those in DAMIP, I recommend at least using the same models across different experiments of the same type (e.g., across the PDRMIP experiments, and within DAMIP) to avoid potential inconsistencies.

Response: We thank the reviewer for this suggestion. We use multi-model simulations in PDRMIP to investigate the impacts of different individual external forcings on winter and summer precipitation over Central Asia and to examine the associated physical mechanisms. We further analyze the attribution of external forcings during the historical period and possible future changes using DAMIP and ScenarioMIP in CMIP6. In the PDRMIP analysis, nine models are available. Among them, CanESM2 and HadGEM2 did not perform regional aerosol experiments, and NCAR-CESM1-CAM4 lacks most of the variables required for this study in the BCx10Asia experiment. When calculating the differences between each forcing experiment and the base experiment, we include all available models with complete data. In the DAMIP historical attribution analysis, we use 18 models previously downloaded in earlier studies to analyze historical precipitation trends. Following the reviewer's suggestion, we additionally provide spatial distributions of precipitation trends using 12 models. As shown in Figure R1, the main conclusions are similar despite differences in the number of models. Therefore, we retain the original results based on a larger model ensemble with 18 models

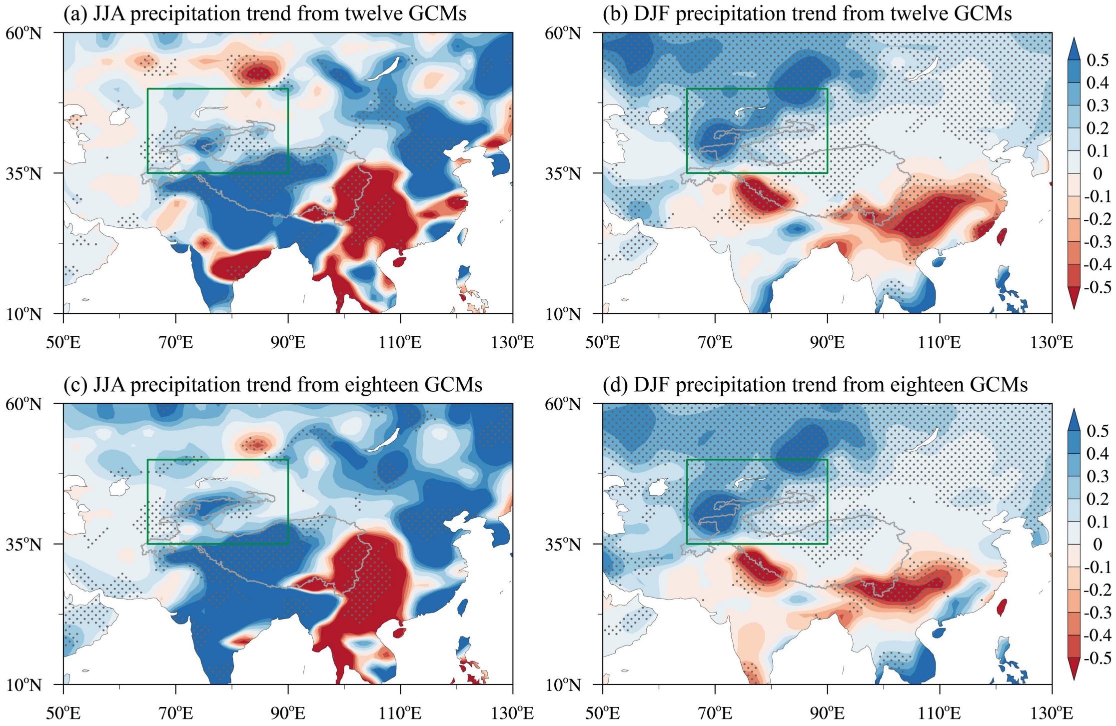

Figure R1. Spatial distribution of precipitation trends over Central Asia from DAMIP historical simulations using different numbers of models. (a) Winter and (b) summer precipitation trends (mm day^{-1} per 100 years) based on 12 models. (c, d) Same as (a, b), but based on 18 models. Thick green boxes delineate the region of Central Asia. The thick gray curves denote Tibetan Plateau terrain height > 2500 m. The gray stippled regions indicate where at least 70% of the models agree on the sign of the trend.

9. The manuscript focuses primarily on the period 1979–2014 to diagnose and attribute seasonal precipitation changes over Central Asia. While this choice is understandable given data availability, the analysis is not sufficiently placed in the context of longer time series, which limits confidence in the attribution of observed trends. Regional precipitation trends over Central Asia are known to be highly sensitive to the start and end years, owing to strong decadal variability. The manuscript does not demonstrate whether the diagnosed trends are robust across

alternative periods (e.g., 1950–2014, 1979–2020, or sliding windows), or whether the selected period coincides with a particular phase of internal variability. Without this context, it is difficult to assess whether the observed increase represents a real long-term forced signal or a transient (internal) fluctuation. There is also some inconsistency in the interpretation between historical and future changes as future trends are diagnosed over a longer period. I recommend for example to show time series extending back to the mid-20th century.

Response: Thanks for your comments. In our manuscript, we focus on the time period from 1979 to 2014 to diagnose and attribute seasonal precipitation changes over Central Asia. To clearly claim this point, we have added a new Figure S13 in Supporting Information to show the time series of regionally averaged precipitation over Central Asia derived from the GPCP (1979–2025), CRU (1950–2024), and GPCC (1950–2019). The linear trends of the the ensemble mean of the three observational datasets indicate an increase in precipitation over Central Asia during 1979–2014 (Supplement Figs. 13). In comparison with 1950–2014 period (0.12 mm day^{-1} per 100 years), it has a larger increasing trend in summer precipitation during 1979–2014 (0.26 mm day^{-1} per 100 years). During this period, anthropogenic aerosol emissions in Asia increased substantially (Ohara et al., 2007; Lu et al., 2011). Since the early 2010s, anthropogenic aerosol optical depth (AOD) in East Asia has decreased markedly due to China's clean air actions and climate policies (Zheng et al., 2018; Samset et al., 2019). It shows a decreasing trend in summer precipitation over Central Asia with -0.16 mm day^{-1} per 100 years, likely due to the effects induced by anthropogenic aerosol reduction. Based on these changes in precipitation trends and the corresponding anthropogenic aerosol emission background, we selected 1979–2014 as the research period.

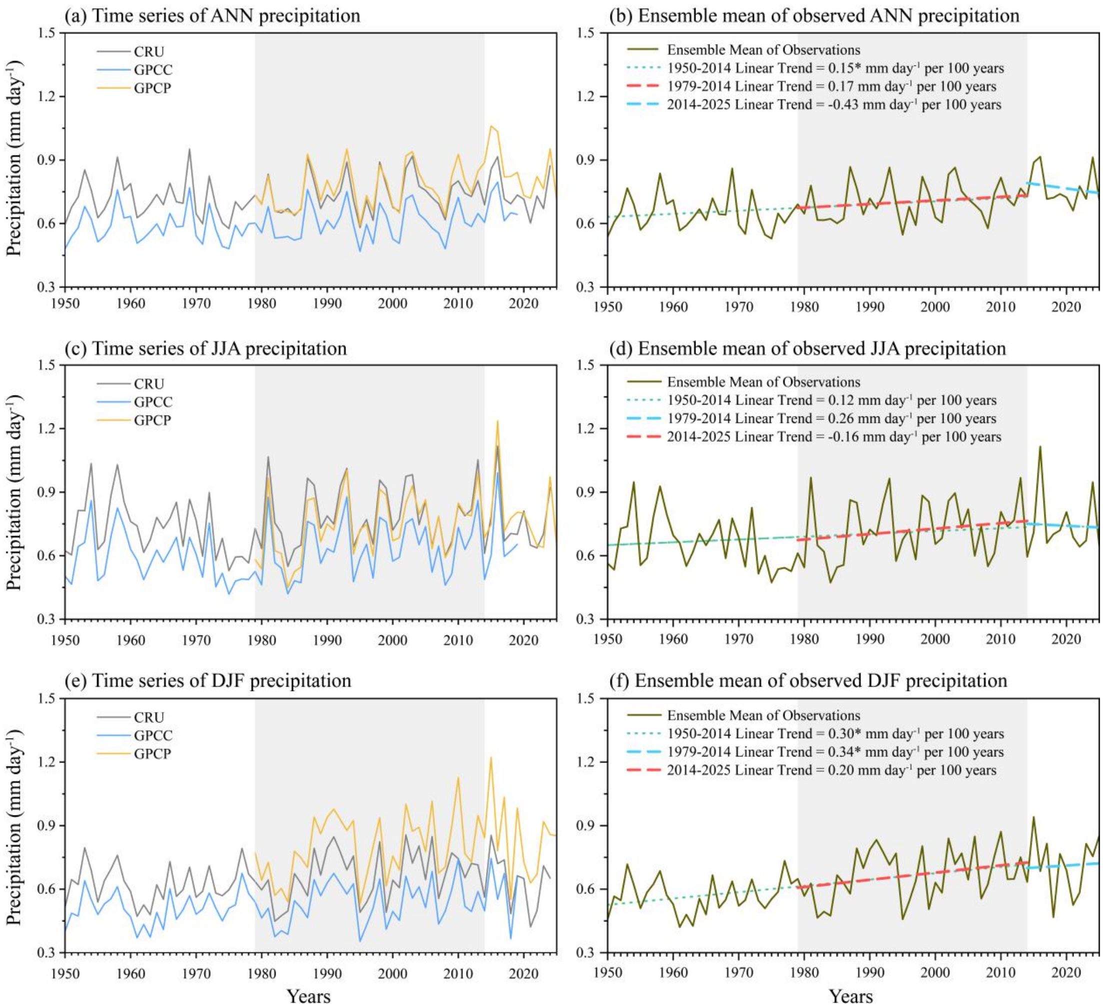

Figure S13. Time series of precipitation over Central Asia derived from GPCP (1979–2025), CRU (1950–2024), and GPCC (1950–2019). (a) Annual precipitation time series from the three observational datasets. (b) Annual precipitation time series of the ensemble mean of the three datasets. (c, d) Same as (a, b), but for winter precipitation. (e, f) Same as (a, b), but for summer precipitation. The dashed lines represent the liner trend in precipitation (mm day^{-1} per 100 years).

10. A key result of the manuscript is the agreement between observations and model-simulated precipitation changes within the defined Central Asia analysis box, particularly in summer. However, this agreement appears to weaken substantially in the surrounding regions in some plots, raising concerns about the spatial robustness of the signal. The proposed mechanisms involve large-scale circulation adjustments (e.g., jet shifts and moisture transport changes), which should manifest as spatially coherent

precipitation anomalies extending beyond the analysis box. While obviously we cannot expect models to capture the precipitation pattern across the entire Asian domain perfectly, the lack of consistent signals in neighbouring regions makes it difficult to reconcile the spatial pattern with the proposed dynamics. This also when accounting for the fact that the signal is not generated by local forcing but somewhat remote to the domain (South or East Asian aerosols). Strong claims that aerosols "dominate" summer precipitation changes may not be fully justified if the signal lacks broader spatial coherence.

Response: Thanks for your comments. Under Asian sulfate aerosol forcing, the strengthening westerlies from the lower to upper troposphere increase vertically integrated moisture transport (Fig. R3a and Supplement Figs. S8a), leading to increased precipitation in North Africa, the Iranian Plateau, and Central Asia (Fig. R3b). This increase in precipitation is consistent with the observed changes (Fig. R3c), indicating spatial consistency in precipitation changes and suggesting the robustness of the simulated response. East Asia and South Asia are mainly influenced by the monsoon system, and the mechanisms controlling precipitation changes are more complex. The spatial patterns differ between models and observations, which may reflect limited model skill in simulating the Asian monsoon (Kang et al., 2002; Chen et al., 2010).

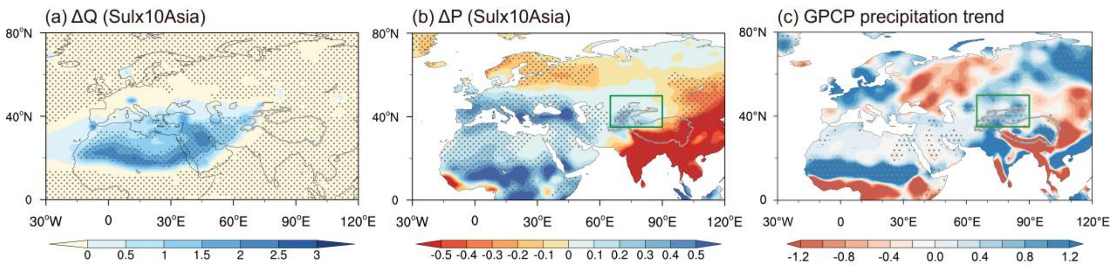

Figure R3. Changes in (a) vertically integrated water vapor and (b) precipitation under the Sulx10Asia forcing, and (c) observed precipitation trends from GPCP. Gray stippling in (a, b) indicates where the multi-model mean of the PDRMIP models is more than 1 standard deviation away from zero. Gray stippling in (c) indicates trends that are statistically significant at the 90% confidence level based on a standard *t*-test.

The region of Central Asia is delineated by thick green boxes. Thick gray curves denote Tibetan Plateau terrain height > 2500 m.

Minor comments

1. The manuscript is generally clear but somewhat long; some repetition could be reduced, particularly in Sections 3.2 and 4.

Response: Thanks for your suggestion. We have reduced the repetition in the main text.

2. Statistical significance is assessed mostly using a comparison with the standard deviation. It is not clear whether this is a standard t-test or the standard deviation refers to something else.

Response: Thank you for pointing this out. In this study, the multi-model mean is used to represent the simulated response, and the inter-model standard deviation is calculated to quantify model spread. When the multi-model mean is more than 1 inter-model standard deviation away from zero, the simulated response is considered robust (Samset et al., 2016; Myhre et al., 2017; Liu et al., 2018). We performed standard *t*-tests to evaluate the statistical significance of linear trends in observed precipitation, regionally averaged precipitation over Central Asia under SSP scenarios, and ERA5 zonal winds.

3. L27: "these sensitivity results that GHG forcing". Something is not correct here.

Response: Sorry for the confusion. We rephrase this sentence as "*Further attribution analysis based on CMIP6 simulations reinforces these sensitivity results and shows that GHG forcing is the primary driver of winter precipitation increases whereas anthropogenic aerosols dominate summer trends.*"

Reference

Allen, M., and Ingram, W.: Constraints on future changes in climate and the hydrologic cycle, Nature, 419, 224–232, https://doi.org/10.1038/nature01092, 2002.

Chen, H., Zhou, T., Neale, R. B., Wu, X., and Zhang, G. J.: Performance of the new NCAR CAM3.5 model in East Asian summer monsoon simulations: Sensitivity to modifications of the convection scheme, J. Clim., 23, 3657–3675, https://doi.org/10.1175/2010JCLI3022.1, 2010.

Deng, J., Dai, A., Xu, H.: Nonlinear climate responses to increasing CO_2 and anthropogenic aerosols simulated by CESM1, J. Clim., 33, 281–301, https://doi.org/10.1175/JCLI-D-19-0195.1, 2020.

Held, I. M., and Soden, B. J.: Robust responses of the hydrological cycle to global warming, J. Clim., 19, 5686–5699, https://doi.org/10.1175/JCLI3990.1, 2006.

Herbert, R., Wilcox, L. J., Joshi, M., Highwood, E., Frame, D.: Nonlinear response of Asian summer monsoon precipitation to emission reductions in South and East Asia, Environ. Res. Lett., 17, 014005, https://doi.org/10.1088/1748-9326/ac3b19, 2021.

Jiang, J., Zhou, T., Chen, X., and Wu, B.: Central Asian precipitation shaped by the tropical Pacific decadal variability and the Atlantic multidecadal variability, J. Clim., 34, 7541–7553, https://doi.org/10.1175/JCLI-D-20-0905.1, 2021.

Kang, I.-S., Jin, K., Wang, B., Lau, K.-M., Shukla, J., Krishnamurthy, V., Schubert, S., Wailser, D., Stern, W., Kitoh, A., Meehl, G., Kanamitsu, M., Galin, V., Satyan, V., Park, C.-K., and Liu, Y.: Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs, Clim. Dyn., 19, 383–395, https://doi.org/10.1007/s00382-002-0245-9, 2002.

Liu, L., Shawki, D., Voulgarakis, A., Kasoar, M., Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Sillmann, J., Aalbergsjø, S. G., Boucher, O., Faluvegi, G., Iversen, T., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T., Shindell, D., and Takemura, T.: A PDRMIP multimodel study on the impacts of regional aerosol forcings on global and regional precipitation, J. Clim., 31, 4429–4447, https://doi.org/10.1175/JCLI-D-17-0439.1, 2018.

Lu, Z., Zhang, Q., and Streets, D. G.: Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010, Atmos. Chem. Phys., 11, 9839–9864, https://doi.org/10.5194/acp-11-9839-2011, 2011.

Myhre, G., Forster, P. M., Samset, B. H., Hodnebrog, Ø., Sillmann, J., Aalbergsjø, S. G., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T. B., Shindell, D., Shine, K. P., Stjern, C. W., Takemura, T., Voulgarakis, A., and Zwiers, F.: PDRMIP: A precipitation driver and response model intercomparison project—Protocol and preliminary results, Bull. Am. Meteorol. Soc., 98, 1185–1198, https://doi.org/10.1175/BAMS-D-16-0019.1, 2017.

Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, Atmos. Chem. Phys., 7, 4419–4444, https://doi.org/10.5194/acp-7-4419-2007, 2007.

Peng, D., and Zhou, T.: Why was the arid and semiarid northwest China getting wetter in the recent decades?, Geophys. Res.-Atmos., 122, 9060–9075, https://doi.org/10.1002/2016JD026424, 2017.

Peng, D., Zhou, T., Zhang, L., and Wu, B.: Human contribution to the increasing summer precipitation in Central Asia from 1961 to 2013, J. Clim., 31, 8005–8021, https://doi.org/10.1175/JCLI-D-17-0843.1, 2018.

Samset, B. H., Lund, M. T., Bollasina, M., Myhre, G., and Wilcox, L.: Emerging Asian aerosol patterns, Nat. Geosci., 12, 582–584, https://doi.org/10.1038/s41561-019-0424-5, 2019.

Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Andrews, T., Faluvegi, G., Fläschner, D., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T., Shindell, D., Shine, K. P., Takemura, T., and Voulgarakis, A.: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study, Geophys. Res. Lett., 43, 2782–2791, https://doi.org/10.1002/2016GL068064, 2016.

Seager, R., Naik, N., and Vecchi, G. A.: Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming, J. Clim., 23, 4651–4668, https://doi.org/10.1175/2010JCLI3655.1, 2010.

Wu, M., Zhou, T., Li, C., Li, H., Chen, X., Wu, B., Zhang, W., and Zhang, L.: A very likely weakening of Pacific Walker Circulation in constrained near-future projections, Nat. Commun., 12, 6502, https://doi.org/10.1038/s41467-021-26693-y, 2021.

Xue, J., Xie, X., and Liu, X.: Differing responses of precipitation in Northern Hemisphere mid-latitudes to increased black carbon aerosols and carbon dioxide, Environ. Res., 210, 112938, https://doi.org/10.1016/j.envres.2022.112938, 2022.

Yao, M., Tang, H., and Huang, G.: Roles of external forcing and internal variability in winter precipitation changes over Central Asia, Earth Future, 13, e2025EF006064, https://doi.org/10.1029/2025EF006064, 2025.

Zhao, Y., Wang, M., Huang, A., Li, H., Huo, W., and Yang, Q.: Relationships between the West Asian subtropical westerly jet and summer precipitation in northern Xinjiang, Theor. Appl. Climatol., 116, 403–411, https://doi.org/10.1007/s00704-013-0948-3, 2014.

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., Peng, L., Qi, J., Yan, L., Zhang, Y., Zhao, H., Zheng, Y., He, K., and Zhang, Q.: Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys., 18, 14095–14111, https://doi.org/10.5194/acp-18-14095-2018, 2018.

Zhong, J., Zhang, X., Zhang, D., Wang, D., Guo, L., Peng, H., Huang, X., Wang, Z., Lei, Y., Lu, Y., Qu, C., Zhang, X., and Miao, C.: Plausible global emissions scenario for 2 °C aligned with China's net-zero pathway, Nat. Commun., 16, 8102, https://doi.org/10.1038/s41467-025-62983-5, 2025.