Response to Review Comments

Dear Editor,

We thank the editor and the second reviewer very much for their further careful review and valuable comments on our manuscript. We have tried our best to address all concerns and revised the manuscript accordingly. Please note that the reviewer's remarks are in black, our response is highlighted in blue, and extracts from the manuscript are in red, with **new texts** that have been added/edited marked in bold. We hope that you find the revision satisfactory. Thank you very much.

Kind regards,
Zhen LIU, on behalf of all co-authors

Responses to Editor:

After attending Laura's EGU talk, where she demonstrated that using only 3 ensemble members might not be sufficient, I am curious to hear your perspective on this matter in relation to the current paper.

Response: Thanks for the comments. We have analyzed the seasonal mean bias and response (JJAS) to Asian aerosols across different ensemble members (Figure R1). While sub-regional details vary from member to member, associated with increased Asian aerosols, all three ensemble members show a tilted dry/wet anomalous rainfall dipole over South Asia, with deficit rainfall over central India and wetting over the northwestern India and the northern Bay of Bengal. Additionally, all members display a wet/dry dipole over Eastern China (Figure R1d–R1f), with some inter-member differences in the orientation of the anomalies (e.g., from zonal bands in Ensemble 2 to northwest to southeast tilted anomalies in Ensemble 3). This general pattern of land precipitation anomalies bears a substantial resemblance to that in the ensemble mean (Fig. 3a–3c in the main text). Similarly, the seasonal mean bias in each ensemble member shows common features and close similarity to that of the ensemble mean. It is worth noting that while the three members are markedly similar over India, they show some differences over China. Ensemble 2 features an extensive zonal wet anomaly over southern China and a less pronounced, yet also zonally-oriented, dry anomaly to the north. The northern drying is more confined in Ensemble 1, which instead features anomalous wetting over central China. Finally, the drying is further confined to the eastern coastline in Ensemble 3, with further wetting inland. Comparing biases and aerosol-induced responses across the ensemble members it is possible to identify a link between their spatial patterns and inter-member similarities/differences. For example, the striking consistency of the bias pattern over India is associated to a similar response pattern in all ensemble members. Similarly, the more tilted anomalous bias in Ensemble 3 is closely similar to the corresponding response, as compared to the strongly zonal structure in Ensemble 2. Based on the mechanistic analysis of the Ensemble mean described in the manuscript, this suggests that the regional monsoon responses to Asian aerosol changes are strongly modulated by the regional precipitation biases: this link is consistent across different ensemble members and discernable despite the influence of internal variability. While this does not discard the possibility of internal variability to affect the monsoon response, the above comparison suggests biases to be crucial (and dominant) in determining the main features of the aerosol-driven changes. Note also that our analysis purposedly focuses on the externally-forced (ensemble mean) response, and not on quantifying its role against internal variability (e.g., as in detection and attribution studies), in light of the importance to better constrain the impact of human-made activities on the monsoon. In this regard, three (transient) ensemble members appear to be enough in our case, possibly because of the pronounced biases of the Met Office model. The longer PDRMIP simulations, and related larger perturbations, still allow for the signal to emerge, despite some models display a smaller bias compared to the Met Office model. It will be interesting to extend this analysis to other models, for example in the context of the new RAMIP experiments.

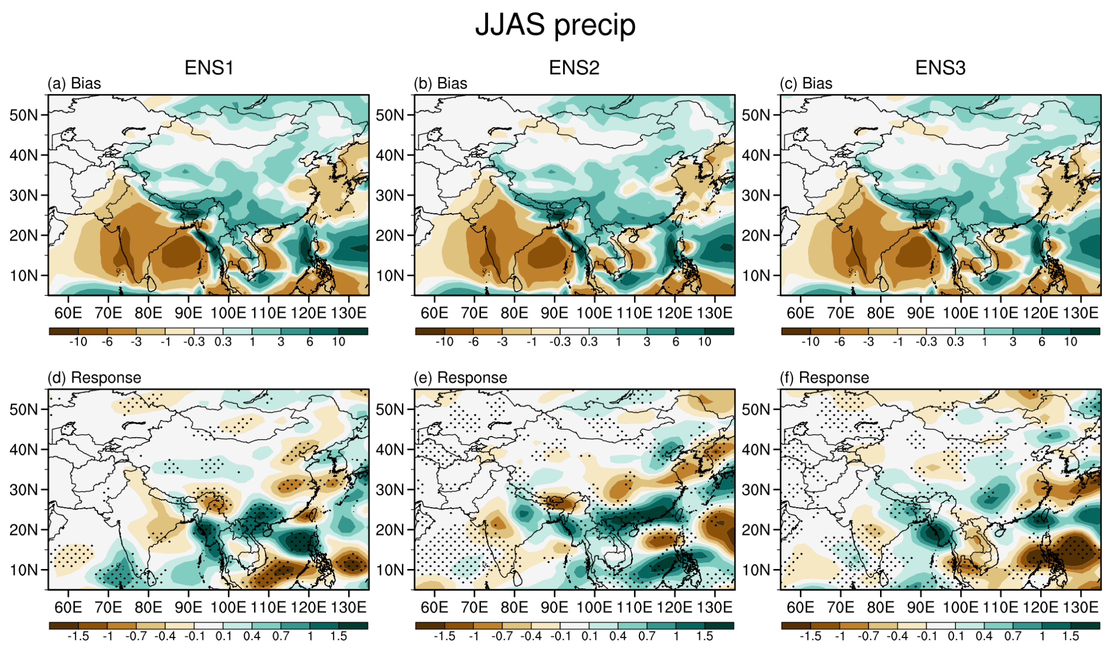

Figure R1. JJAS precipitation (mm day^{-1}) bias (first row) and response (second row) to Asian anthropogenic aerosols (difference between CONT and CONTfA averaged during 2003–2012) in each ensemble member. Black dots mark grid-points for which the difference is significant at the 90% confidence level.

Responses to Reviewer #2:

1. Fig. 1 evaluates the model performance in simulating precipitation and circulation, which shows the precip difference is between 6 to 10 mm/day vs. its climatology between 10 to 15 over Bay of Bengal, equivalent to ~50% of the climatology. This is a significant underestimation. I suggest the authors show the difference of precipitation in percent and perform a quantitative evaluation of model performance rather than a description of the difference.

Response: Thank you for the additional comments and suggestions. We have replaced the absolute precipitation differences with percentage differences (Figure R2c). Indeed, the model displays a considerable underestimation of precipitation amounts by 60% compared to observed climatological values over India and the Bay of Bengal. To the east, there are wet biases ranging from 20 to 60% of the climatology over southwestern China, and even up to 80% of climatological rainfall over the northwestern subtropical Pacific. We have included this figure and related description in the main text as follows:

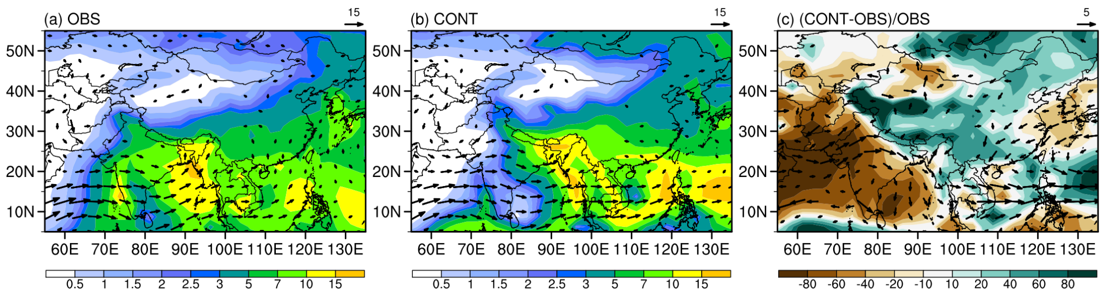

Figure R2. June–September average precipitation (mm day^{-1}) and 850-hPa wind (m s^{-1}) for the observations (GPCP and CMAP average for precipitation, ERA5 for wind), the control simulation, and their differences (precipitation differences in percentage and wind differences in absolute values) during the period 1993 to 2012.

Lines 179–187: "Figure 1 compares the 1993-2012 June–September average precipitation and 850-hPa winds in the control simulation to observations (GPCP and CMAP average for precipitation, ERA5 for wind). The model reproduces the broad characteristics of the observed rainfall and circulation patterns (pattern correlation of 0.80 for precipitation, which is significant at the 99.9% confidence level). The difference panel indicates that the model **underestimates the rainfall amount by 60% over India and the Bay of Bengal** due to a weaker southwesterly monsoon flow. **To**

the east, there are wet biases ranging from 20 to 60% of the observed climatology over southwestern China, and even up to 80% over the northwestern subtropical Pacific, associated with enhanced cyclonic flow. Note that this bias pattern is common across CMIP6 models, although the magnitude of the anomalies varies from model to model (Wilcox et al., 2020), and is also consistent with that in the historical simulations of the CMIP6 Met Office model (Rajendran et al., 2022). A thorough discussion of the model bias and its linkage to regional and remote circulation can be found in Liu et al. (2021)."

2. And Figure R3 does not support that aerosol-cloud interactions play an more important role, because aerosol-cloud interaction in part means cloud responses to aerosols via aerosols working as cloud nuclei. Figure R3 does not shown cloud responses to aerosols. The contrasting meteorological patterns in June and September could be caused by many factors, and aerosol-cloud interactions are not the only candidate.

Response: Thank you for the comments. The differences between CONT and CONTfA represent the total responses to changes in Asian anthropogenic aerosols, including both aerosol-radiation and aerosol-cloud interactions. As shown in Figure R3 (Figure R3 of previous revision), the aerosol-mediated changes in radiation show a similar pattern between June and September with minor changes through the season. This suggests that the contrasting aerosol-induced responses in precipitation and circulation (Fig. 5 in the main text) are likely modulated by aerosol-cloud interactions. The accompanied cloud responses to aerosols changes have been discussed in the Fig. 7 and Fig. 8 of the main text. We have toned down the role of aerosol-cloud interactions as the reviewer suggested in the first round of revision.

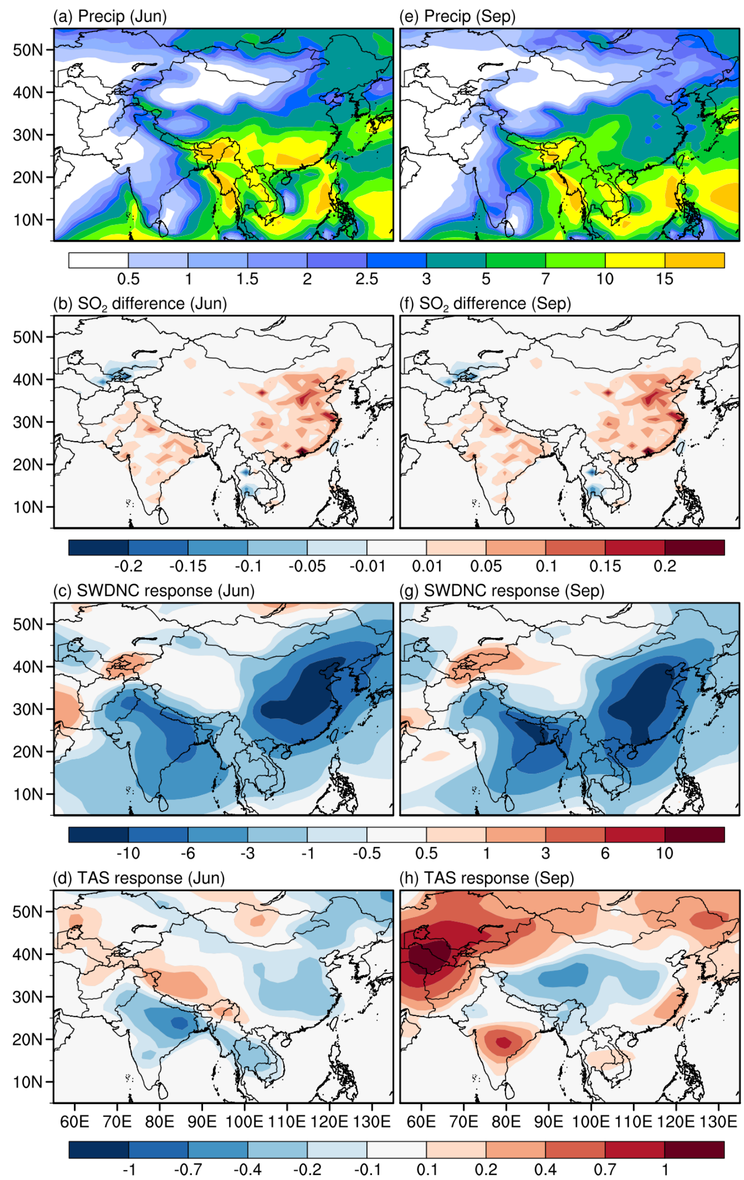

Figure R3. (a) The June climatological precipitation (mm day^{-1}) in CONT. June differences in (b) SO_2 emissions (Tg yr^{-1}), (c) clear-sky downward shortwave radiation (W m^{-2}), and (d) near-surface temperature (K) between CONT and CONTfA. (e–h) Same as (a–d) but for September.