Dear Referee,

Thanks for giving us an opportunity to revise our manuscript (ID: egusphere-2023-407). We appreciate your positive and constructive comments. We have studied these comments carefully and make revisions on the manuscript. We believe that the manuscript has benefited substantially from this revision with much clearer presentation. These comments and the corresponding replies are listed below.

The reviewer's comments are highlighted by gray. The symbol "≫" quotes the original texts in the manuscript. Followed by the comments are our responses (normal texts) and current texts in the manuscript (**leaded by line number in the manuscript with the tracked changes**). Some important revisions are colored by red.

With regards,

Chenwei Fang*, Jim M. Haywood, Ju Liang, Ben T. Johnson, Ying Chen and Bin Zhu*

Replies to Referee#2

General Comments:

1. I would suggest the authors add more discussions, especially for section 3.1 and 3.2, to clarify a bit more. The authors tend to only describe the figures very briefly and don't give much explanation (dynamical mechanism) to the changes induced by reductions in scattering and absorbing aerosols. Most of the content for Fig. 3 is introduction of the method. Maybe the authors can put method/calculation related content to section 2 so that there is more room for detailed discussion. The interpretation is blended with method, which is easy to get lost. There is also little discussion related to Fig. 4 and 5.

Thank you for this valuable suggestion. We agree that the descriptions about the definition for monsoon onset and withdrawal are more like the research background of this study. There is also a lack of discussions related to Fig. 3-6. According to your suggestions, we (1) moved the descriptions about the definition for monsoon onset and withdrawal to the Methods section and made it a sub-section (Lines 182-206); (2) added more quantitative descriptions and made a comparison between the SASM adjustments calculated based on the W2009 and N2016 in Lines 271-286, 309-324 (for Fig. 3-5); (3) added more quantitative descriptions and made a comparison between the EASM adjustments calculated based on W2016 and G1983 in Lines 294-308, 333-335 (for Fig. 3, 4 and 6).

(1) **Lines 182-206 (Methods)**

2.3 Definitions for monsoon onset and withdrawal

Monsoon transition is usually referred to as the seasonal shift of wind direction between the dry and wet seasons (Zhao et al., 2006). The change of some key climatic variables in the monsoon region is often used to define the onset and withdrawal pentad (5-day mean) or onset and withdrawal day for both the SASM and EASM (e.g., He and Zhu, 2015; Noska and Misra, 2016; Wang, D. et al., 2016). Note that the SASM and the continental part of the EASM are regarded as tropical and subtropical monsoons, respectively, and their seasonal wind reversals are mainly characterized by the changes of zonal and meridional winds (Sun and Ding, 2011). In this study, the monsoon duration and the precipitation for the duration is obtained by calculating the monsoon onset and withdrawal dates. The monsoon onset/withdrawal dates are derived according to the definitions given in previous studies. The monsoon changes were calculated based on different definitions as there are significant variations in these parameters under different definitions.

The definitions from Wang et al. (2009) and Noska and Misra (2016), hereafter referred to as W2009 and N2016, are adopted to obtain the SASM onset and withdrawal dates. W2009 uses 850-hPa zonal wind averaged over South Asia (5-15°N, 40-80°E) as an onset circulation index (OCI) of the SASM, and the date of onset is defined as the first day when OCI exceeds 6.2 m s^{-1}. N2016 uses All-India rainfall (AIR) to calculate the cumulative pentad mean anomaly $C'_m(i)$ of AIR for pentad i of year m: $C'_m(i) = \sum_{n=1}^{i}[AIR_m\,(n) - \bar{\bar{C}}]$, where $\bar{\bar{C}}$ is the climatology of the annual mean of AIR over N (=72 based on UKESM1's calendar) pentads for M (=2) years. The onset/withdrawal of SASM is defined as the day after $C'_m(i)$ reaches its absolute minimum/maximum. Definitions from Wang, D. et al (2016) and Guo (1983), hereafter referred to as W2016 and G1983, are applied to calculate the EASM monsoon duration and precipitation. The 850-hPa meridional wind (V_{850}) over East Asia was used in W2016 to determine the EASM onset and withdrawal: (1) the onset pentad of the EASM is the pentad when V_{850} over East Asia starts to be greater than 0 m s^{-1} (i.e. a net southerly component) and remains positive in the subsequent three pentads (or the average V_{850} of the accumulative four pentads is greater than 0.5 m s^{-1}) ; (2) the withdrawal pentad of the EASM is the pentad when V_{850} turns negative (i.e. a net northerly component). The EASM onset/retreat pentad based on G1983 was calculated as the difference between the sea level pressures over land (represented by 110°E) and sea (represented by 160°E) over East Asia.

(2) Lines 271-286 and Lines 309-324 (comparison between the SASM adjustments calculated based on the W2009 and N2016)

Lines 271-286

Note that using different definitions of monsoon onset/withdrawal dates may result in the variations in the monsoon duration response range although the SASM duration and precipitation adjustments in W2009 and N2016 are qualitatively consistent. The SASM durations in N2016 from different simulation sets are basically 4-5 pentads longer than those in W2009 (Fig. 3a and b). The SCT-driven extension of the SASM duration based on N2016 (2 pentads) is also much longer than that in W2009 (0.4 pentads). The difference in the SASM duration adjustments between W2009 and N2016 can be attributed to the distinct selection of monsoon feature to characterize the monsoon subseasonal variations. Syroka et al (2004) pointed out that the withdrawal of the SASM defined by the precipitation is much late than that defined by the monsoon circulation due to the late decrease in precipitation in southern India. The precipitation continues to increase in southern Indian after September associated with the winter monsoon (Bhanu Kumar et al., 2004), while the SASM-related circulation characteristics becomes unclear in the meantime. Therefore, the SASM onset dates based on N2016 is roughly the same with those based on W2019, but the withdrawal date is about 5 pentads later, resulting in the longer monsoon duration (Fig. 4a and b). Moreover, there exists an additional enhancement of monsoon precipitation over SA in the "SCT" set, which further leads to the later SASM withdrawal and longer SASM duration in N2016 (Fig. 4b). Besides, the precipitation during early autumn is sensitive to the location and synoptic/sub-synoptic systems (tropical cyclones, depressions, easterly waves, north-south trough activity and coastal convergence, etc; Bhanu Kumar et al., 2004), which possibly contributes to the larger variation range in the monsoon withdrawal date in N2016.

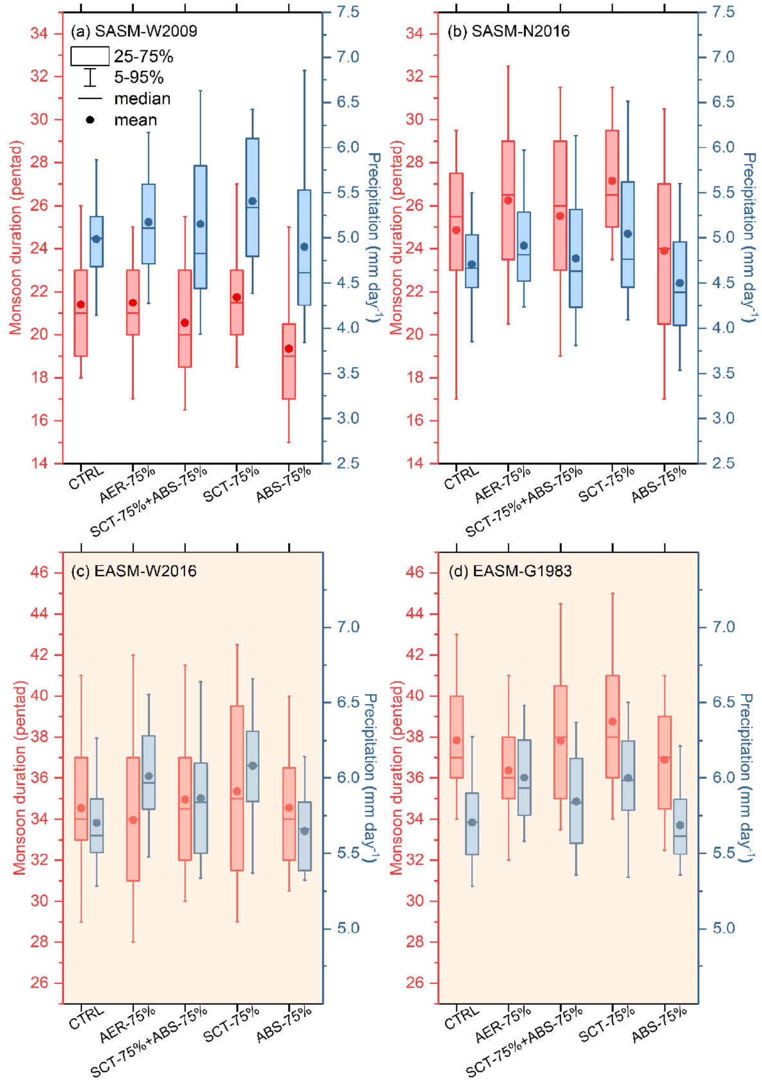

Figure 3: Box diagrams of the monsoon duration (red; unit: pentad) and precipitation (blue; unit: mm day^{-1}) over South Asia (a and b) and East Asia (c and d) in different simulations. Dots and middle horizontal lines inside boxes indicate mean and median values, respectively, and lower and upper sides of boxes indicate 25 and 75% range, respectively, and top and bottom line represent 5% and 95%, respectively. The boxes labelled SCT-75+ABS-75% in each panel are the linear addition of the impacts of the reductions in the SCT and ABS. Panel (a) is derived based on the definition from Wang et al. (2009; hereafter referred to as W2009). Panel (b) is derived based on the definition from Noska and Misra (2016; hereafter referred to as N2016). Panel (c) is derived based on the definition from Wang, D. et al (2016; hereafter referred to as W2016). Panel (d) is derived based on the definition from Guo (1983; hereafter referred to as G1983).

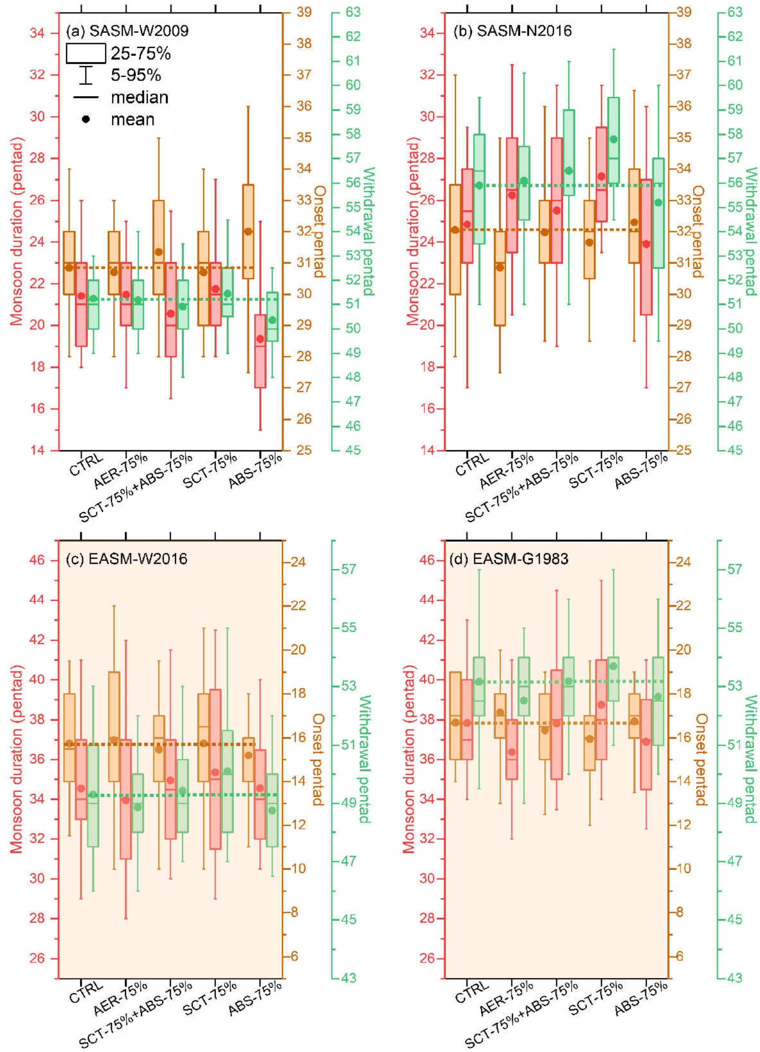

Figure 4: Same as Figure 3, but for the monsoon onset dates (yellow; unit: pentad), withdrawal dates (green; unit: pentad) and duration (red; unit: pentad). The yellow and green dashed lines denote the mean values of monsoon onset and withdrawal in the CTRL simulation set, respectively.

Lines 309-324

Fig. 5 and 6 show the spatial patterns of the opposing changes in the precipitation and the 850-hPa circulation of the SASM and EASM induced by the SCT and ABS reductions. The monsoon precipitation changes over SA are consistent in W2009 and N2016, showing significantly increased (decreased) precipitation due to SCT (ABS) reduction.

The low-level SASM circulation is also enhanced (weakened) over the Indian peninsular with the reduced SCT (ABS) based on W2009, while the wind response is different in N2016. The wind field adjustment in N2016 is characterized by a weak southwesterly anomaly over the north-central part of the Arabian Sea (north of 20°N) but an easterly anomaly over the south India and south Arabian Sea (10-20°N). The enhancement of easterly flow over SA could be associated with the relatively late monsoon withdrawal dates (58th pentad; Table S1) based on N2016 in the "SCT" set. The continuously increasing precipitation related to winter monsoon in the southern part of SA after September (Syroka et. al, 2004) and the SCT-reduction-induced increased precipitation in SA (Fig. 4g) jointly lead to the delay of the SASM withdrawal date to October based on N2016. At this time, the low-level circulation over south SA and south Arabian Sea is dominated by the prevailing easterly (October-December; Sengupta and Nigam, 2019) although the local precipitation remains elevated, and is associated with the summer monsoon precipitation according to the N2016. Hence, the onset is better defined than the withdrawal based on the precipitation definition adopted in N2016, especially over southern SA. The W2009 definition is more widely applicable over SA, and the summer monsoon precipitation increase is more logically coherent with the circulation enhancement based on this definition.

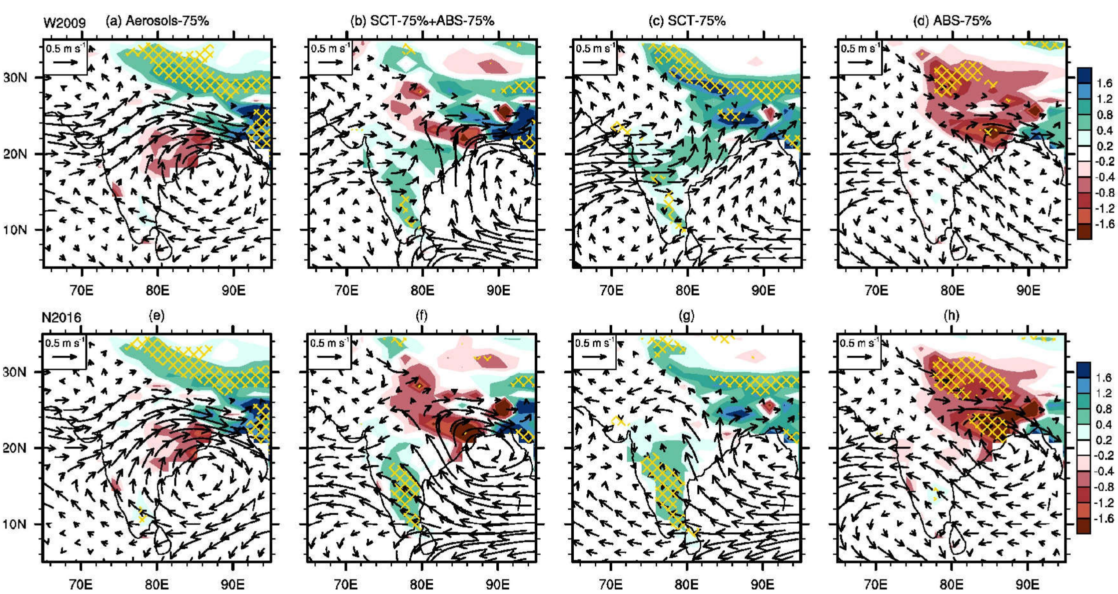

Figure 5: Spatial distributions of the monsoon precipitation (shading; unit: mm day^{-1}) and 850-hPa wind fields (vector; unit: m s^{-1}) responses to the reductions in total aerosols (a and e), scattering aerosols (SCT; c and g) and absorbing aerosols (ABS; d and h) over South Asia. Panels (b) and (f) are the linear addition of the impacts of the reductions in the SCT and ABS. Hatched regions denote where the precipitation change is statistically significant at the 95% confidence level according to a Wilcoxon rank sum test. Panels (a)-(d) are derived based on the definition from W2009. Panels (e)-(h) are derived based on the definition from N2016. The

SASM adjustments forced by emission reductions in different aerosol types are the difference between the aerosol-emission-perturbed and control runs.

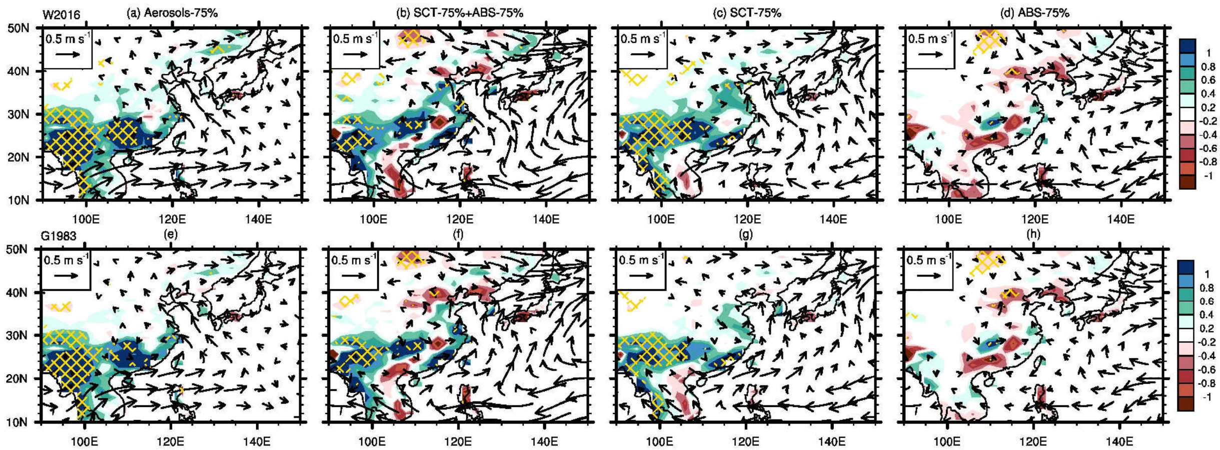

Figure 6: Same as Figure 5, but for East Asia. Panels (a)-(d) are derived based on the definition from W2016. Panels (e)-(h) are derived based on the definition from G1983.

(3) Lines 294-308 and Lines 333-335 (comparison between the EASM adjustments calculated based on the W2016 and G1983)

Lines 294-308

The impacts of reducing SCT and ABS on the EASM in terms of timescale and intensity (here is characterized by precipitation amount) are similar to that on the SASM, except that the reduction in total aerosols slightly shortens the temporal extent of the EASM (more pronounced in G1983) and increases the summer precipitation over the EASM-controlled region (Fig. 3c and d). The monsoon duration is extended by about 1 pentad both in W2016 and G1983 due to the reduction in SCT, which is mainly from the monsoon withdrawal deferment (Fig. 4c and d). Reduction in ABS oppositely advances the withdrawal, leading to a shorter monsoon (1 pentad in G1983) in East Asia. Compared to the distinguishable EASM withdrawal adjustments, the SCT- or ABS-reduction induced EASM onset adjustments calculated by W2016 (based on meridional wind) and G1983 (based on land-sea pressure difference) are not obvious and consistent, indicating the complexity of EASM onset. He et al. (2008) also pointed out that the EASM exhibits a progressive and complicated establishment and a swift withdrawal. The EASM onset date is postponed but the withdrawal date is advanced due to the total aerosol reduction, hence the EASM temporal extent is shortened a little (0.5 pentads in W2016 and 1.4 pentads in G1983). Compared to the EASM adjustments in W2016, the EASM show longer duration (about 3 pentads) in G1983 due to the later withdrawal (about 4 pentads). Zhu et al. (2012) has clarified that the climatological transition date of the zonal land-sea contrast in autumn over EASM-controlled region is about 3 pentads later than that of the monsoon circulation, which largely explained the relatively late monsoon withdrawal dates in G1983.

Lines 333-335

……Overall, the EASM adjustments in terms of the temporal extent and intensity calculated based on G1983 are basically consistent with the results based on the W2016, in spite of the relatively late monsoon withdrawal dates in G1983, which adopts the land-sea pressure difference as the key monsoon characteristic.

2. It is interesting to see the linearity/non-linearity when combing reductions in both scattering and absorbing aerosols. However, I would give a second thought about discussing this mostly in the last result section (sect. 3.4). The authors can either blend this section with other sections and give an overall discussion in the conclusion section or at least say a few words about the linearity in other sections.

Thank you for this valuable suggestion. We have moved the discussions about the Asian monsoon responses in the linear addition and those in the simulation of reducing total aerosols to the end of each sub-section (Lines 356-380; Lines 423-428; Lines 487-488) and given an overall discussion in the conclusion section (Lines 548-563).

Lines 356-380 (Section 3.2 Response of monsoon temporal extent and intensity)

Future global emission reductions of the SCT and ABS aerosols may not be synchronous due to the differences in contributing region and sector sources, technological progress and air pollution policies (Li, H. et al., 2022; Rao et al., 2017). However, the SASM and EASM responses to the reductions in total aerosols may not be a linear summation of the impacts of the reductions in individual aerosol type due to the nonlinearity of the atmospheric systems. Therefore, we compare the results summed from the sensitivity experiments of reducing SCT or ABS alone with those of reducing both of them simultaneously to estimate the importance of the nonlinear atmospheric adjustments on the monsoon changes in the future and investigate the respective theoretical impacts of simultaneous or non-simultaneous emission reductions of the SCT and ABS aerosols on the Asian region.

Generally, the pattern of the anomalous precipitation and monsoon horizontal circulation over SA by adding the results of reducing SCT and ABS aerosols are similar to the results of reducing total aerosols, especially for the W2009 (Fig. 5). However, the precipitation north of 30°N shows a reduction in the validity of the linear addition assumption compared to the precipitation change in the simulation of reducing total aerosols, although most of the reduced precipitation does not pass the significance test ($p < 0.05$). There's also significantly increased precipitation over the southern part of SA in the linear addition, which is contributed by the impacts of SCT reduction. Additionally, an easterly anomaly appears over the Arabian Sea (10-20°N) in N2016 (Fig. 5f) as the linear addition of Fig. 5g and 5h, while an SASM westerly flow is enhanced over this region in the simulations of reducing total aerosols (Fig. 5e). The dominated impacts of SCT reduction and non-linear effects between the SCT and ABS contribute to the enhanced SASM westerly in Fig. 5e. The general feature of precipitation and circulation responses over the EA continent (north of 15°N) in the linear addition are also consistent with that in the simulation of simultaneous SCT and ABS reductions (Fig. 6), except for the insignificant decreased precipitation contributed by the impacts of ABS reduction (Fig. 6b and 6f). For the quantitative results of regional precipitation adjustments, the linear addition results show an increased precipitation in both SA and EA compared with the CTRL results (Fig. 3). The increased precipitation amount is less than the results of total aerosol reduction due to the simple addition of precipitation change caused by ABS reduction. However, the results of linear addition are inconsistent with the total aerosol reduction results in terms of the SASM and EASM duration variations, indicating that the impacts of reducing SCT or ABS alone on monsoon subseasonal variability cannot be simply added up.

Lines 423-428 (Section 3.3.1 Responses of land-sea contrast)

For the adjustments of air temperature (Fig. 7) and land-sea SLP difference (Fig. 8) in the linear addition, their general features are also coherent with the results of reducing the total aerosols, yet there exist differences in details. For example, there is a significant SLP increase in the Northwestern Pacific Ocean in Fig. 8f due to the simple addition of the impacts of SCT and ABS reductions from Fig. 8g and 8h while reduction in total aerosols induces insignificant SLP changes over this region (Fig. 8e). Nonetheless, both results of linear addition and reducing total aerosols yields negative anomalies of land-sea SLP difference during monsoon season.

Lines 487-488 (Section 3.3.2 Responses of the upper-tropospheric systems)

Besides, it is found that the linear addition can capture the feature of geopotential height (Fig. 9), upper-tropospheric jet (Fig. 11), moisture divergence field (Fig. 12) and SAH (Fig. 13) adjustments over Asia induced by total aerosols reduction.

Lines 548-563 (Conclusions and discussions)

The spatial features of the linear summation of the individual effect from reducing SCT or ABS alone is similar to the effect of reducing both aerosol types simultaneously. However, differences in details between the linear summation and the results of reducing total aerosols indicates some non-linearity in the system as a whole. Various complex non-linear interactions in the atmosphere (the mixing states of the SCT and ABS aerosols, the nonlinear changes in cloud fields induced by activated aerosols and other feedback from atmospheric thermal and dynamic processes) could contribute to the deviation. The difference of the monsoon precipitation and circulation anomalies related to the atmospheric adjustments between the results from linear addition and the simulation with total aerosol reduction is more pronounced over South Asia compared to that over East Asia, indicating that the climate adjustments over South Asia show higher degrees of non-linear additivity. However, the non-linearity hardly affects the general pattern of the Asian monsoon and monsoon-related large-scale environmental adjustments caused by short-term aerosol emission reductions. Considering the unpredictable technological progress and policies, the emission reduction pathways of scattering and absorbing aerosol components are possibly non-synchronous. The opposite adjustments of Asian rainy season forced by scattering and absorbing aerosol emission control and the performance of their linear summation need to be considered during the climate and environment policy-making process.

3. How would the model biases, such as in precipitation and monsoon onset/withdraw, affect the signals from perturbed simulations? For example, the overview paper of UKESM1 by Stellar et al. (2019) shows considerable low biases of precipitation in JJA over South Asia.

Thank you for this valuable suggestion. We have added a figure (Fig. S2; Lines 27-33) in the Supplement presenting the UKESM1 bias in precipitation over Asia. We have also added the discussions about the impacts of model uncertainties in monsoon precipitation and onset/withdraw on our simulated results in the Conclusions and discussions Section (Lines 572-606).

Lines 27-33 (Fig. S2; Supplement with tracked changes)

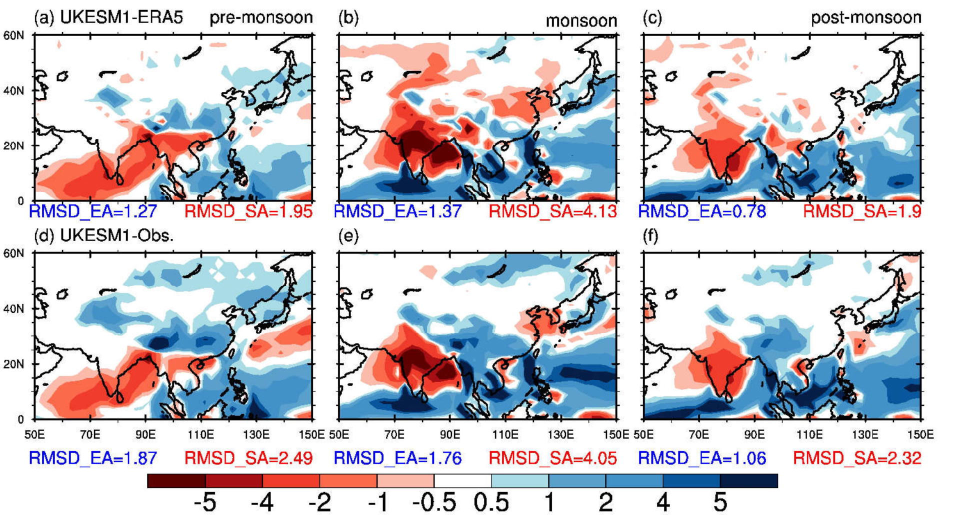

Figure S2. Spatial distributions of the climatological mean (1985-2014) root-mean-square deviation (RMSD; unit: mm day^{-1}) between the simulations and ERA5 reanalysis (a-c) during pre-monsoon (April-May; a), monsoon (June-August; b) and post-monsoon (September-October; c) seasons. (d)-(f): Same as (a)-(c), but for the RMSD between the simulations and merged observations from Global Precipitation Climatology Project (GPCP) rain gauge-satellite combined precipitation dataset and Climate Prediction Center (CPC) unified gauge-based daily observations. The regional mean RMSD values over EA and SA are shown in blue and red text, respectively.

Lines 572-606 (Conclusions and discussions)

Additionally, bias may exist in the results of monsoon response due to the model performance in reproducing the monsoonal characteristics. General circulation models are often noted to have biases in the seasonal means of monsoon features (such as the precipitation). Jain et al. (2019) showed that the CMIP5 models show a prominent dry bias over northern and central SA in summer. The RMSD values of the simulated summer monsoon precipitation over SA land range from 3.50 to 8.54 mm day^{-1} among the CMIP5 models with respect to the observations in their evaluations. However, CMIP5 models tend to overestimate the precipitation in most regions of China, and the RMSD of the annual mean precipitation for the multi-model means is 3.98 mm day^{-1} relative to the GPCC observations (Chen and Frauenfeld, 2014). The higher daily mean precipitation amount may lead to higher RMSD values in China if the evaluation is only conducted in boreal summer. UKESM1 is a CMIP6 era model that was developed from the CMIP5 era HadGEM2-ES model. The precipitation biases of CMIP6 and CMIP5 models align closely at the spatiotemporal scale, though CMIP6 models show an improvement in reducing the precipitation bias in the Yangtze River valley, part of North China, Western Ghats and North-East foothills of Himalayas (Gusain et al., 2020; Xin et al., 2020). Here, we summarize the RMSD between the UKESM1 results and ERA5 reanalysis/observation in Fig. S2. Consistent with the

CMIP5's bias on precipitation shown in previous research, UKESM1 yields an overall overestimation over EA but underestimation over SA. The RMSD values reach maximum during monsoon season over EA (1.37 - 1.76 mm day^{-1}) and SA (4.05 - 4.13 mm day^{-1}). The simulated bias of UKESM1 for monsoon precipitation over SA is at the lower end of the RMSE range from CMIP5 models, and the overestimation over EA is also lower than the multi-model means. Tian et al. (2021) pointed out that the UKESM1 is one of the CMIP6 models that exhibits better reproduction of historical precipitation over China. In addition, the signal of possible monsoon responses shown in this study are estimated by subtracting the aerosol-emission-perturbed runs from control runs by assuming that the systematic error in both the control and the aerosol-emission-perturbed simulations remains the same, and this assumption is inherent in most climate change studies.

Moreover, the positive climate change signal in Asian monsoon precipitation as well as the enhanced circulation in the future due to total aerosol reduction shown in this study is qualitatively consistent with the findings of previous research either focusing on the short-term impacts of COVID-19 lockdown (Kripalani et al., 2021) or long-term impacts of future emission scenarios (Zhao et al., 2018; Wilcox et al., 2020). The possible Asian monsoon adjustments regulated by reduction in SCT/ABS component further examined in this study are also the direct opposite of the SASM (Krishnamohan et al., 2021; Sherman et al., 2021) or EASM (Jiang et al., 2013; Xie et al., 2020) changes forced by the industrial SCT/ABS emission increase. Besides, the definitions used in this study for the EASM (W2016 and G1983) and SASM (W2009) have been validated the ability to show the monsoon onset for the historical period in previous research (Fang et al., 2020; Khandare et al., 2022). The N2016 index has also been verified to show consistent seasonal evolution with other dynamic and thermodynamic variables of the SASM (Noska and Misra, 2016). Based on the Community Atmosphere Model version5.1, Wang, D. et al (2016) showed an EASM onset delay and withdrawal advance caused by the SCT, and vice versa for the ABS. Kripalani et al. (2021) found that the summer monsoon withdrawal over India was delayed in 2020, which could be associated with the reduced aerosol during COVID-19 lockdown. All these findings support the signals of short-term air pollution mitigation on the SASM and EASM adjustments in terms of the temporal extent shown in this study.

4. Have the authors looked at the impact of reducing local (with SA and EA) anthropogenic emissions versus the impact of reducing anthropogenic emissions outside of the two regions? How much of the changes in SASM and EASM are induced by the reduction of local anthropogenic emissions?

Thank you for this valuable suggestion. We agree that the issue of local versus global reductions in aerosol emissions and how the local versus aerosols transported into the region from other sources outside of the region of investigation is an interesting one. However, the focus of the paper would be considerably changed if we were to follow the suggestion of including additional simulations investigating this impact which would make the paper rather too long. We therefore suggest that the best way forward is to include a caveat in the discussion and conclusion (Lines 628-632) that highlights this issue as a potential area of future work.

Lines 628-632 (Conclusions and discussions)

This work focusses on the impacts of global reductions of SCT and ABS aerosols to examine the potential dynamical feedbacks and impacts on monsoon characteristics. A further area of research that is not pursued here is the role of local reductions of aerosol emissions (i.e. in the areas of investigation) versus reductions in aerosol concentrations outside of the areas of investigation. While this is outside the scope of this paper, further work is suggested in this area to better understand the role of changes in local versus remote aerosol emissions.

Specific comments:

5. Lines 116-117, what do you mean by "includes the physical core climate model of"? Could you rephrase it?

≫ Lines 116-117: The modelling system includes the physical core climate model of HadGEM3-GC3.1 (Hadley Centre Global Environment Model version 3; Kuhlbrodt et al., 2018; Williams et al., 2018) and the UKCA model (U.K. Chemistry and Aerosols model; Archibald et al., 2020; Mulcahy et al., 2018), along with terrestrial carbon and nitrogen cycles, dynamic vegetation and interactive ocean biogeochemistry.

We have rephrased this sentence, as shown below:

Lines 117-121

The modelling system is built on top of the core physical model HadGEM3-GC3.1 (Hadley Centre Global Environment Model version 3; Kuhlbrodt et al., 2018; Williams et al., 2018) and interactively coupled with the atmospheric components UKCA model (U.K. Chemistry and Aerosols model; Archibald et al., 2020; Mulcahy et al., 2018), terrestrial biogeochemistry and ocean biogeochemistry.

6. Lines 143-144, just would like to check that anthropogenic emissions of SO2, OM, and BC are reduced globally, not just for South and East Asia, right?

≫ Lines 143-144: In the “Total” set, all anthropogenic emissions of SO2, organic matter (OM) and BC were reduced by 75% relative to the SSP3-7.0 scenario.

Yes, aerosol emissions were perturbed globally. We have added the relevant descriptions in the Methods section.

Lines 146-147

To investigate the theoretical impacts that short-term pollution mitigation may have, three other sets of simulations were performed in which aerosol emissions were perturbed globally in different ways.

7. Line 156, what do you mean by “different random perturbations in the stochastic physics”? Perturbing temperature of the initial state? Could you be more specific?

≫ Lines 156: To create the 10 member ensembles within each set the individual simulations ran with different random perturbations in the stochastic physics, causing the atmospheric flow to diverge into different meteorological realizations.

Thank you for this valuable suggestion. The description about the stochastic physics has been added in the Methods section.

Lines 161-168

To create the 10 member ensembles within each set the individual simulations ran with different random perturbations in the stochastic physics, causing the atmospheric flow to diverge into different meteorological realizations. The stochastic physics introduces small random perturbations to the wind fields, temperature and moisture tendencies from some of the sub-grid parameterizations schemes including convection, gravity-wave drag, radiation and large-scale cloud microphysics. These perturbations are applied in a way that conserves energy, momentum and moisture but represents variability and uncertainty in unresolved physical processes, which has been shown to improve ensemble predictions on medium-range (Palmer et al., 2009; Tennant et al., 2011), seasonal (Weisheimer et al., 2011) and decadal timescales (Doblas-Reyes et al., 2009).

8. Lines 178-179, I would suggest the authors mention Fig. S1 here or even before to explain the definition of the two domains.

≫ Lines 178-179: As our study involves the sub-seasonal variations in monsoon onset and withdrawal, the monthly comparisons among South and East Asia precipitations from CPC and GPCP observations, ERA5 reanalysis and the UKESM1 simulations are shown in Fig. 1.

Thank you for this valuable suggestion. The description about Fig. S1 has been moved to the part of Model evaluation.

Lines 212-214

As our focus is primarily on the monsoon, here the model performance is evaluated by comparing against observations of the regional precipitation over South and East Asia. The division of South and East Asia (Fig. S1) used in this study follows Iturbide et al. (2020), which is adopted by IPCC (2021).

9. Line 215, missing a space between Cm and of.

≫ Lines 215: N2016 in Fig. 3(b) used All-India rainfall (AIR) to calculate the cumulative daily anomaly $C'_m(i)$of AIR for day i of year m:……

We feel sorry that we did not thoroughly check the format detail. The space has been added.

Lines 196

N2016 uses All-India rainfall (AIR) to calculate the cumulative pentad mean anomaly $C'_m(i)$ of AIR for pentad i of year m:……

10. Lines, 272-274, the conclusion seems to be too general, and may not be the situation for both EASM and SASM. For example, how about the increase of SLP over China in Fig. 8c?

≫ Lines 272-274: The SCT reduction induced land warming yields a lower SLP anomaly over Asia continent compared with that over Indian and western Pacific oceans, which is favourable for the early/late transition of land-sea pressure difference in pre/post-monsoon season and a stronger SASM and EASM circulation in monsoon season.

≫Fig. 8:

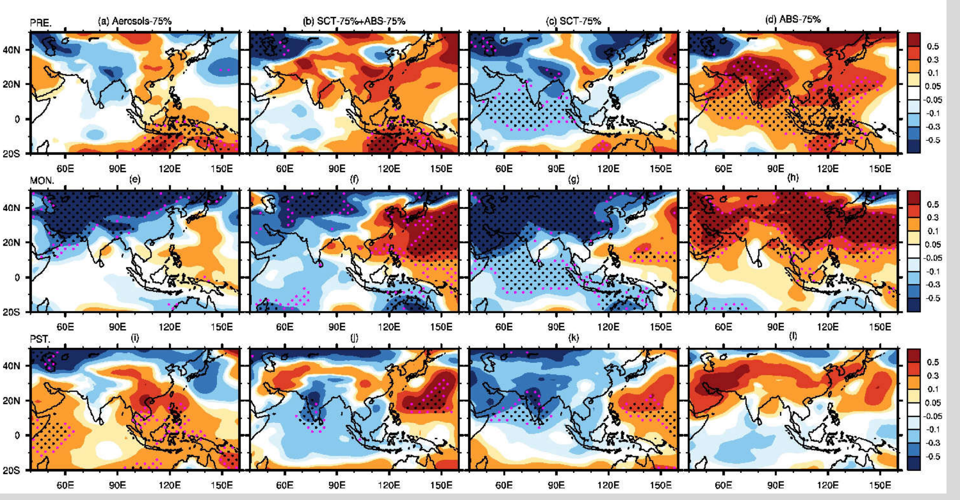

Figure 8: Spatial distributions of the sea level pressure (unit: hPa) responses to the reductions in total aerosols (a, e and i), SCT aerosols (c, g and k) and ABS aerosols (d, h and l) over Asia during pre-monsoon (April-May; a-d), monsoon (June-August; e-h) and post-monsoon (September-October; i-l) seasons. Panels (b), (f) and (j) are the sum of the impacts of the reductions in the SCT and ABS. Black and pink dotted regions denote where the sea level pressure change is statistically significant at the 95% and 90% confidence level, respectively, according to a t-test.

Sorry, we didn't make it clear. According to your suggestions, (1) We have modified the Fig. 8 in order to show the changes in sea level pressure (SLP) caused by aerosol emission reductions more intuitively. Only the SLP changes with a confidence level of 95% or 90% according to the t-test are shown in the new Fig. 8 (Lines 1032-1038). The increase of SLP over China in original Fig. 8 (c) is insignificant and not shown in new Fig. 8 (c); (2) We have added a new figure (Fig. S3 in Supplement; Lines 48-56) to quantitatively examine the anomalous land-sea SLP difference between the Asian continent and its surrounding oceans and seas; (3) We have added more analysis and made a more careful statement about the impacts of SCT reduction on SLP changes over Asian continent and its adjacent oceans and seas in Lines 393-405.

Lines 1032-1038 (new Figure 8)

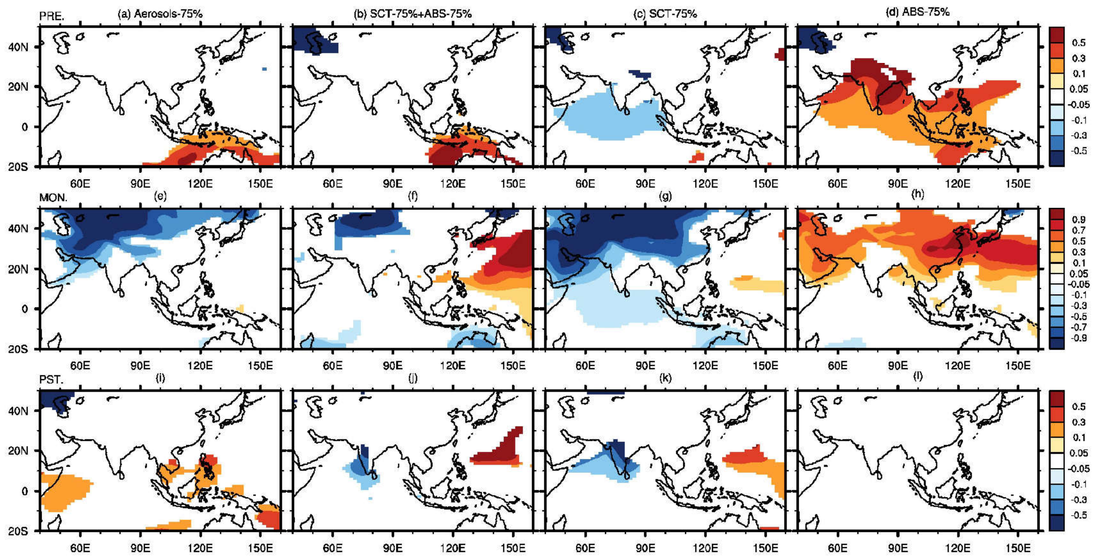

Figure 8: Spatial distributions of the sea level pressure (unit: hPa) responses to the reductions in total aerosols (a, e and i), SCT aerosols (c, g and k) and ABS aerosols (d, h and l) over Asia during pre-monsoon (April-May; a-d), monsoon (June-August; e-h) and post-monsoon (September-October; i-l) seasons. The sea level pressure responses are the difference between the aerosol-emission-perturbed and control runs. Panels (b), (f) and (j) are the sum of the impacts of the reductions in the SCT and ABS. Only the sea level pressure changes with a confidence level of 95% or 90% according to the t-test are shown.

Lines 48-56 (Fig. S3; Supplement with tracked changes)

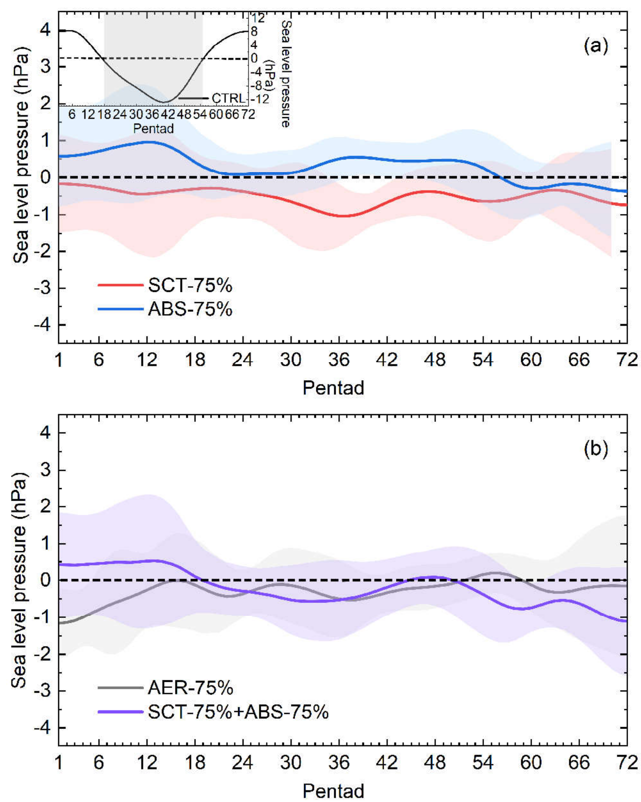

Figure S3. Time series of the anomalous land-sea sea level pressure (SLP) difference (unit: hPa) between the Asian continent part (including South Asia, East Asia, Tibet Plateau and East-Central Asia) adjacent to the ocean and its surrounding oceans and seas (including Northwest Pacific, tropical Indian Ocean, Bay of Bengal and Arabian Sea) to the reductions in total aerosols (b; gray line), SCT aerosols (a; red line) and ABS aerosols (a; blue line). The x-axis denotes the time (unit: pentad). The land-sea SLP difference responses are the difference between the aerosol-emission-perturbed and control runs. Purple line in Panel (b) represent the sum of the impacts of the reductions in the SCT and ABS. The shading area denote the standard deviation of the land-sea SLP difference anomaly. The sub-panel attached to Panel (a) gives the climatological land-sea SLP difference (unit: hPa) from control simulations. The region division used in this study refers to the sixth IPCC assessment report and is shown in Fig. S1.

Lines 393-405

The SCT reduction induced land warming reduces the SLP over Asia continent but increase the SLP over Northwest Pacific (Fig. 8c, g and k). The quantitative results of the anomalous land-sea SLP difference between the Asian continent and its surrounding oceans and seas are shown in Fig. S3. The SCT reduction induces a negative land-sea SLP difference anomaly throughout the year (Fig. S3 and Fig. 8c, g and k), which is favourable for the advance in the land-sea SLP difference transition from positive to negative in spring and the delay in the transition from negative to positive in autumn. The negative anomalous land-sea SLP difference also leads to bigger land-sea SLP contrast and a stronger SASM and EASM circulation in the monsoon season. Note that the SLP changes in part of the oceanic areas adjacent to the SA region are consistent with the continental SLP changes, albeit with a smaller range of decrease (Fig. 8c, g and k). This could potentially be attributed to the reduced ACT that transported from Asian continent. However, the SLP decrease over these oceanic areas exerts negligible influence on the overall SCT-reduction-induced anomalous negative land-sea SLP difference between the Asian continent and adjacent oceans (Fig. S3).

11. Lines, 279-282, I would argue that Fig 8a seems to be more close to Fig 8c, indicating SCT dominating. Fig. 8i does not like Fig. 8j-l, indicating strong non-linearity?

≫ Lines 279-282: In addition, the anomalous land-sea SLP gradient between the Asian continent and the Indian and the western Pacific Oceans caused by the short-term total aerosols mitigation during monsoon season is dominated by the SCT aerosols and enhances the monsoon circulation over South and East Asia (Fig. 8e). In other seasons except summer, the land-sea SLP adjustments over Asia is controlled by the combined effects of SCT- and ABS-reductions (Fig. 8a and 8i).

Thank you for this valuable suggestion. We have added more analysis and made a more careful statement. We have added discussions about the Fig. 8 (a and i; see 10th Reply) and the dominant effects in regulating the SLP responses over Asian continent and its surrounding oceans and seas in Lines 411-421.

Lines 411-421

In addition, the anomalous land-sea SLP difference between the Asian continent and the topical Indian and Northwest Pacific Oceans caused by the short-term total aerosols mitigation during monsoon season is dominated by the SCT aerosols and enhances the monsoon circulation over South and East Asia (Fig. 8e). There is also a negative land-sea SLP difference anomaly due to the total aerosols mitigation in pre- and post-monsoon seasons (Fig. S3b), which is governed by the impacts of SCT-reduction. However, the spatial pattern of SLP adjustments during pre-monsoon season induced by total aerosol reduction shows a SLP increase over the seas of Southeast Asia, and both the impacts of SCT- and ABS-reduction (Fig. 8 c and d) contribute to the SLP increase over this region. Besides, the ABS-reduction has no significant impacts on the SLP adjustments during post-monsoon season (Fig. 8i). But the regions with significant SLP changes caused by total aerosol reduction are also inconsistent with those caused by the SCT reduction (Fig. 8i and k), indicating the strong non-linearity of atmospheric system.

12. Lines 295-300, should it be "atmospheric warming associated with the SCT reduction" according to Figure 7? Should it be "The geopotential height increases in the uppermost troposphere …" instead of "The pressure .."? I would argue that it is not so obvious in Figure 9 that the geopotential height changes strengthens the poleward pressure gradient force in the north flank of this area.

≫ Lines 295-300: Coherent with the temperature perturbations shown in Fig. 7, both the geopotential height changes over South and East Asia during monsoon season caused by the emission reduction of total aerosols are dominated by the atmospheric cooling associated with the SCT reduction. The pressure increases in the uppermost troposphere (200-500 hPa) north of 40°N over South and East Asia, which strengthens (weakens) the poleward pressure gradient force in the north (south) flank of this area.

Thank you for your correction. The relevant description has been corrected. Besides, the meridional gradient of geopotential height responses to aerosol reductions has also been added into Fig. 9 and Fig. S4 in order to intuitively display the changes in pressure gradient force.

Lines 439-443

Coherent with the temperature perturbations shown in Fig. 7, both the geopotential height changes over South and East Asia during monsoon season caused by the emission reduction of total aerosols are dominated by the atmospheric warming associated with the SCT reduction. The geopotential height increases in the uppermost troposphere (200-500 hPa) around 40°N over South and East Asia, which strengthens (weakens) the poleward pressure gradient force in the north (south) flank of this area.

Lines 1040-1047 (Figure 9)

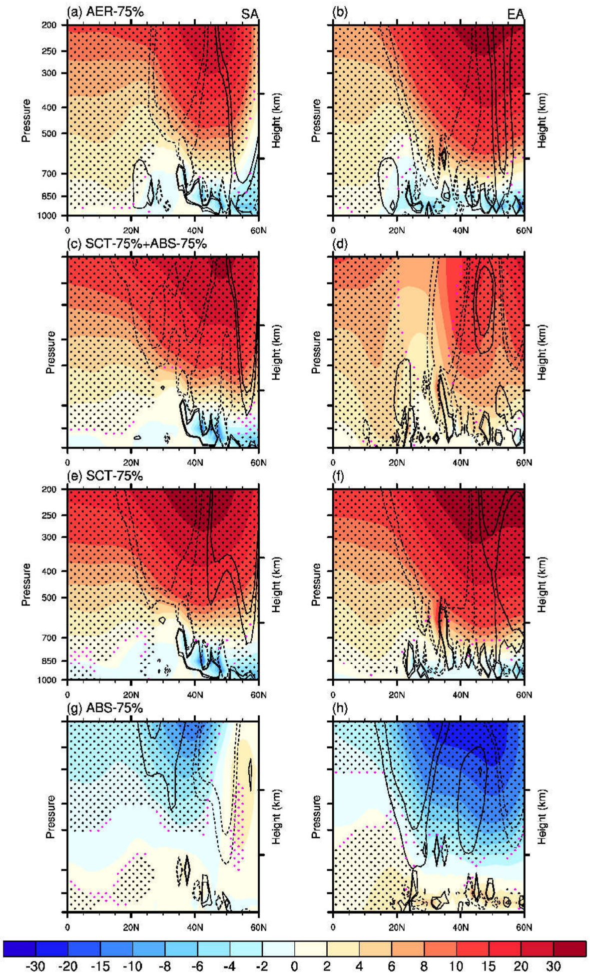

Figure 9: Zonal-mean geopotential height (unit: gpm) responses to the reductions in total aerosols (a and b), SCT aerosols (e and f), and ABS aerosols (g and h) during monsoon season over South Asia (70-90°E; a, c, e and g) and East Asia (100-120°E; b, d, f, h). Monsoon season is analyzed and based on the definitions from W2009 over South Asia and W2016 over East Asia. The geopotential height responses are the difference between the aerosol-emission-perturbed and control runs. Panels (c) and (d) are the sum of the impacts of the reductions in the SCT and ABS. Black lines denote the meridional gradient of GH response (unit: gpm m^{-1}; solid and dashed lines denote positive and negative values, respectively). Black and pink dotted regions denote where the geopotential height change is statistically significant at the 95% and 90% confidence level, respectively, according to a t-test.

Lines 60-67 (Figure S4; Supplement)

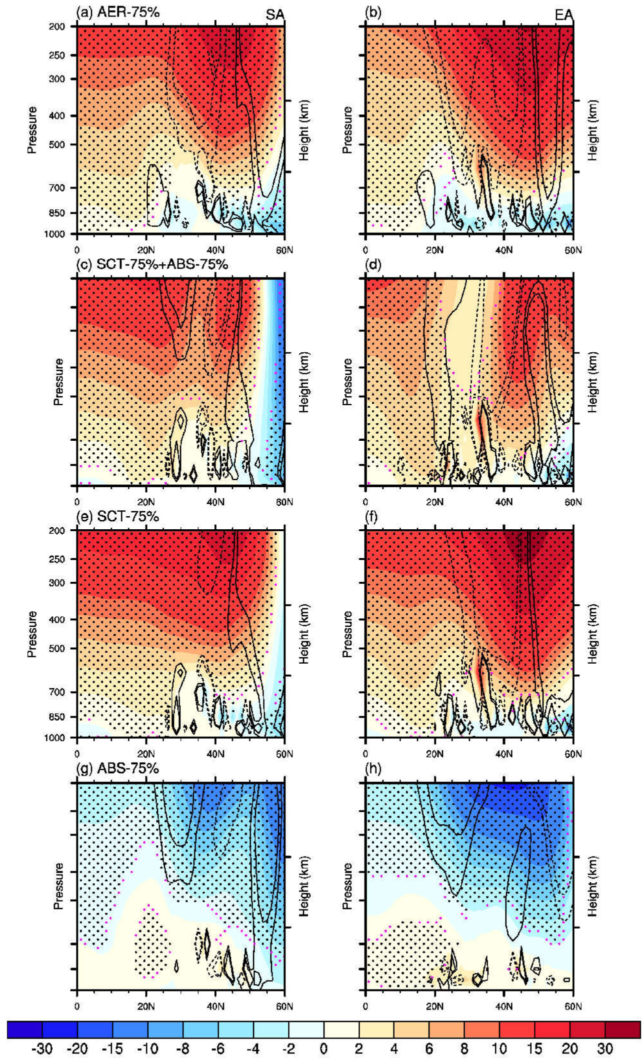

Figure S4. Zonal-mean geopotential height (unit: m) responses to the reductions in total aerosols (a and b), scattering (SCT) aerosols (e and f), and absorbing (ABS) aerosols (g and h) during monsoon season over South Asia (70-90°E; a, c, e and g) and East Asia (100-120°E; b, d, f, h). Monsoon season is analyzed and based on the definitions from N2016 over South Asia and G1983 over East Asia. Panels (c) and (d) are the sum of the impacts of the reductions in the SCT and ABS. Black lines denote the meridional gradient of GH response (unit: gpm m^{-1}; solid and dashed lines denote positive and negative values, respectively). Black and pink dotted regions denote where the geopotential height change is statistically significant at the 95% and 90% confidence level, respectively, according to a t-test.

13. Line 345, should be “may not be a linear summation of”?

≫ Lines 345: The SASM and EASM responses to the reductions in total aerosols may not a linear summation of the impacts of the reductions in individual aerosol type due to the nonlinearity of the atmospheric systems.

Sorry, this is a grammatical mistake. We have corrected the sentence.

Lines 358-359

However, the SASM and EASM responses to the reductions in total aerosols may not be a linear summation of the impacts of the reductions in individual aerosol type due to the nonlinearity of the atmospheric systems.

14. Lines 384-393, I would suggest the authors state the impacts for SCT and ABS in two separate sentences instead of putting antonyms in parentheses. It is easy to get lost when reading long sentences.

≫ Lines 384-393: The warming (cooling) induced by the SCT (ABS) reduction over South and East Asia during pre- and post-monsoon seasons favors early (late) transition of land-sea thermal contrast and SLP gradient in spring and late (early) transition in autumn, thus extending (shortening) the monsoon by advancing (delaying) its onset and delaying (advancing) the withdrawal. The change in pressure gradient force induced by SCT (ABS) aerosol reduction leads to an increase (decrease) in westerlies to the north of the upper-tropospheric jet center, leading to the northward (southward) displacement of the high-level easterly and westerly jet. The northward (southward) displacement of the high-level jet causes the anomalous moisture convergence (divergence) and upward (downward) motion at the lower level over north India and east China, eventually enhancing (weakening) the precipitation over South and East Asia during monsoon season. The stronger (weaker) SAH due to the land warming (cooling) induced by the reduction of SCT (ABS) also facilitates (hinders) the local convective development over northern South Asia and southern East Asia.

Thank you for this valuable suggestion. We have clarified the impacts of scattering (SCT) and absorbing (ABS) aerosols in two different sentences.

Lines 532-543

The warming induced by the SCT reduction over South and East Asia during pre- and post-monsoon seasons favors early transition of land-sea thermal contrast and SLP difference in spring and late transition in autumn, thus extending the monsoon by advancing its onset and delaying the withdrawal. The change in pressure gradient force induced by SCT aerosol reduction leads to an increase in westerlies to the north of the upper-tropospheric jet center, leading to the northward displacement of the high-level easterly and westerly jet. The northward displacement of the high-level jet causes the anomalous moisture convergence and upward motion at the lower level over north India and east China, eventually enhancing the precipitation over South and East Asia during monsoon season. The stronger SAH due to the land warming induced by the reduction of SCT also facilitates the local convective development over northern South Asia and southern East Asia. However, ABS reduction acts in the opposite sense in Asian climate responses, which delays the transition of land-sea contrast in spring and advancing the transition in autumn, forces the Asian jet to move southward, and weakens the SAH intensity.

15. Figure 2, I would suggest changing the title for middle column to be MON to be consistent with PRE and PST. Or maybe it is better to just pre-monsoon, monsoon, and post-monsoon.

≫ Figure 2:

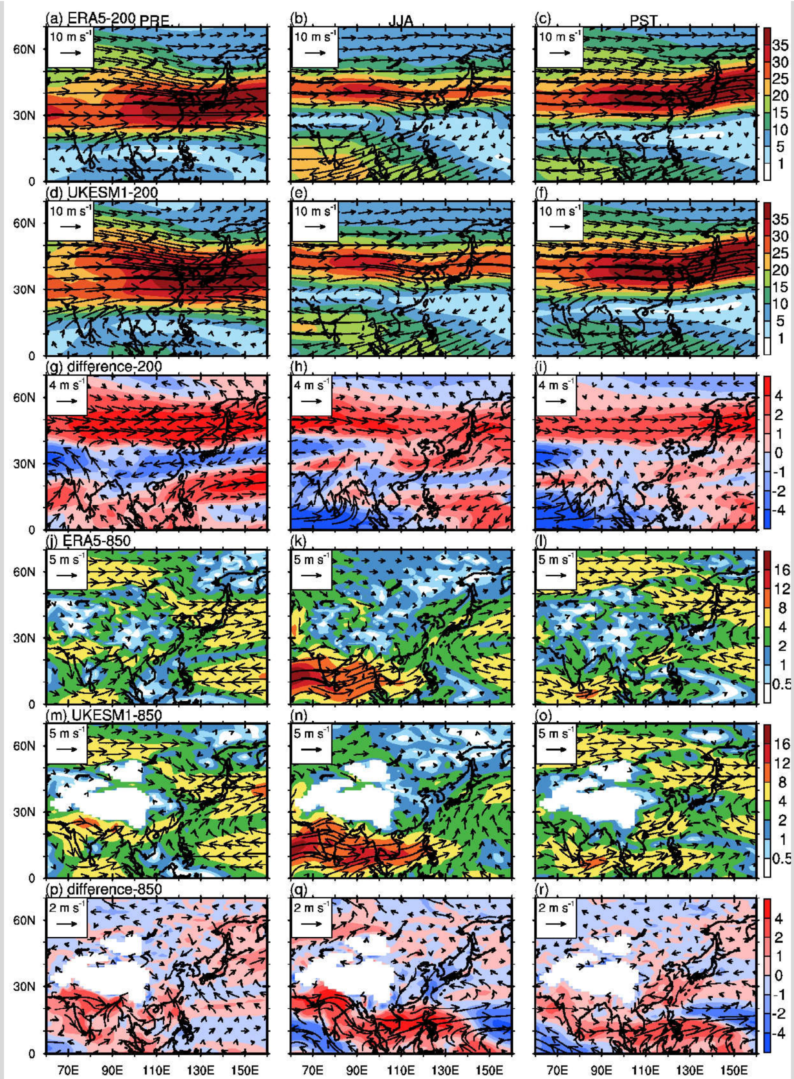

Figure 2: Spatial distributions of the climatological mean (1985-2014) wind directions (vectors; unit: m s^{-1}) and wind speeds (shading; unit: m s^{-1}) at 200 hPa (a-i) and 850 hPa (j-r) from ERA5 reanalysis (a-c and j-l) and CMIP6-UKESM1 historical simulation (d-f and m-o) over Asia during pre-monsoon (April-May; a, d, g, j, m and p), monsoon (June-August; b, e, h, k, n and g) and post-monsoon (September-October; c, f, i, l, o and r) seasons. Panels (g-i) and (p-r) show the differences between the wind fields from the UKESM1 simulation and ERA5 reanalysis at 200 hPa and 850 hPa, respectively.

Thank you for this valuable suggestion. We have unified the titles of the three columns in Fig. 2.

Lines 981-986

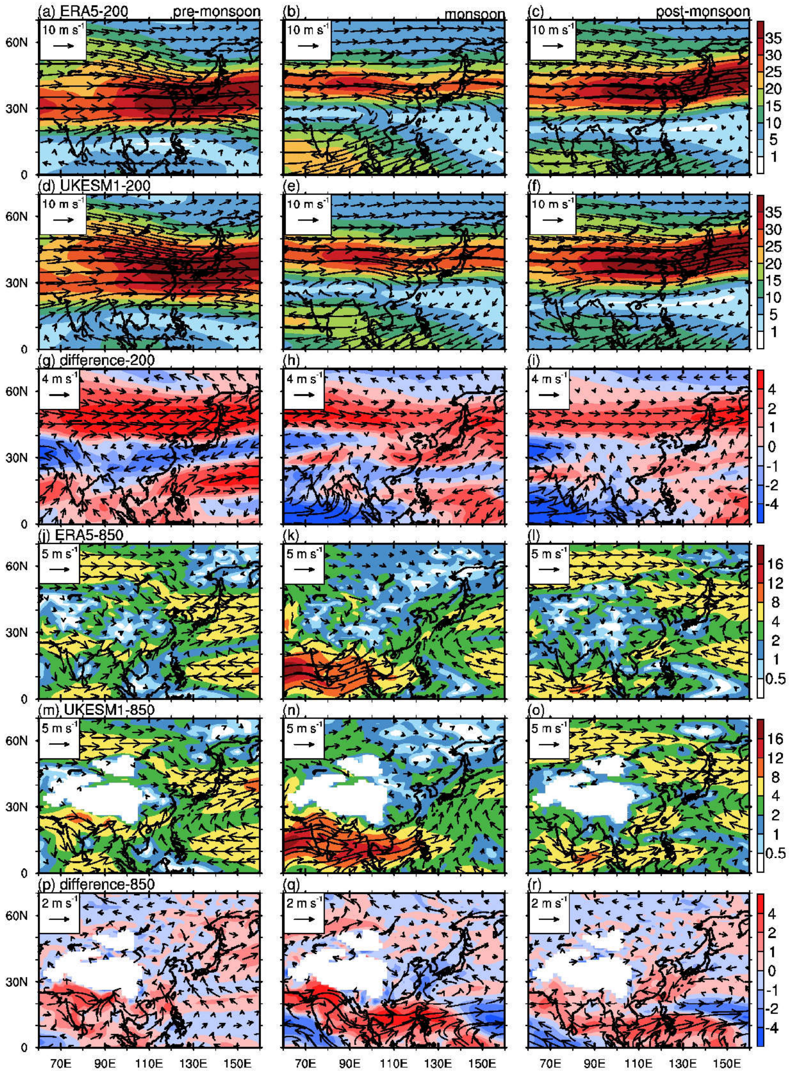

Figure 2: Spatial distributions of the climatological mean (1985-2014) wind directions (vectors; unit: m s^{-1}) and wind speeds (shading; unit: m s^{-1}) at 200 hPa (a-i) and 850 hPa (j-r) from ERA5 reanalysis (a-c and j-l) and CMIP6-UKESM1 historical simulation (d-f and m-o) over Asia during pre-monsoon (April-May; a, d, g, j, m and p), monsoon (June-August; b, e, h, k, n and g) and post-monsoon (September-October; c, f, i, l, o and r) seasons. Panels (g-i) and (p-r) show the differences between the wind fields from the UKESM1 simulation and ERA5 reanalysis at 200 hPa and 850 hPa, respectively.

16. Figure 3, could you change scale for left y-axis of panel b from day to pentad? It may be clearer to compare panel a and b. Is it possible to add values showing linearly combined SCT-75% and ABS-75%?

≫ Figure 3:

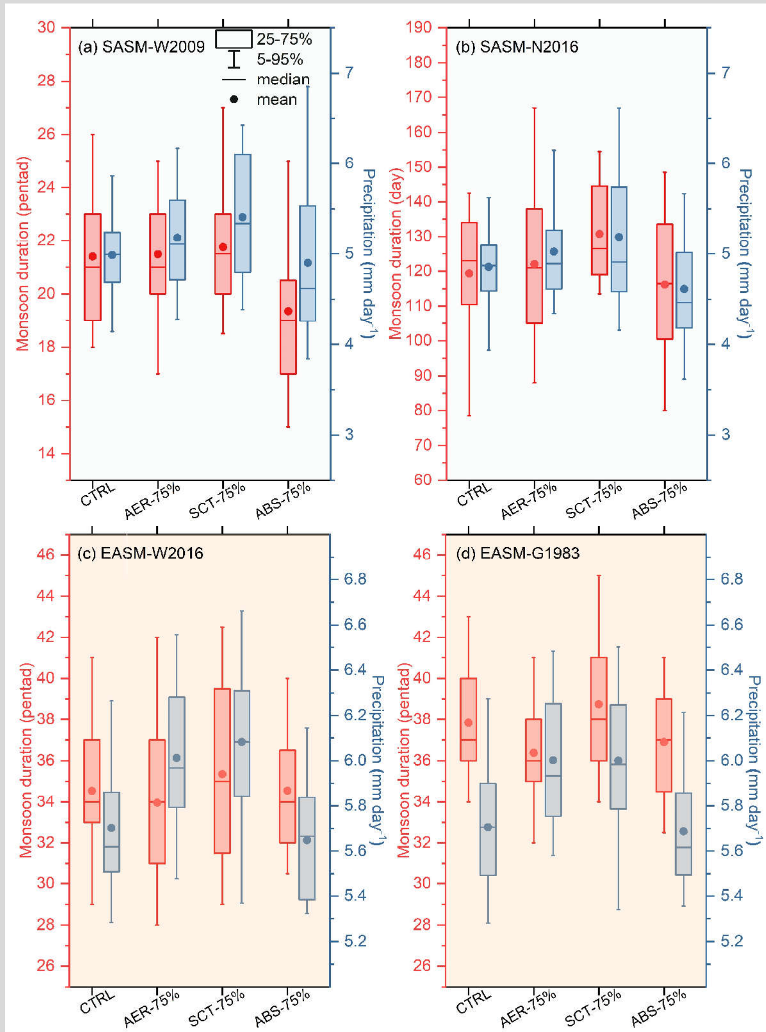

Figure 3: Box diagrams of the monsoon duration (red; unit: pentad for a, c and d, day for b) and precipitation (blue; unit: mm day^{-1}) over South Asia (a and b) and East Asia (c and d) in different simulations. Dots and middle horizontal lines inside boxes indicate mean and median values, respectively, and lower and upper sides of boxes indicate 25 and 75% range, respectively, and top and bottom line represent 5% and 95%, respectively. Panel (a) is derived based on the definition from Wang et al. (2009; hereafter referred to as W2009). Panel (b) is derived based on the definition from Noska and Misra (2016; hereafter referred to as N2016). Panel (c) is derived based on the definition from Wang, D. et al (2016; hereafter referred to as W2016). Panel (d) is derived based on the definition from Guo (1983; hereafter referred to as G1983).

Thank you for this valuable suggestion. The scale for left y-axis of Fig. 3(b) has been changed from day to pentad. The comparison between the Fig. 3(a) and (b), the comparison between the Fig. 3(c) and (d) and the relevant discussions have been added in Lines 271-286 and Lines 305-308. The linear addition of the impacts of the reductions in the SCT and ABS has also been added in Fig. 3. The relevant descriptions about the linear addition of the impacts of reductions in the SCT and ABS are added in Lines 364-380.

Lines 988-996 (Figure 3)

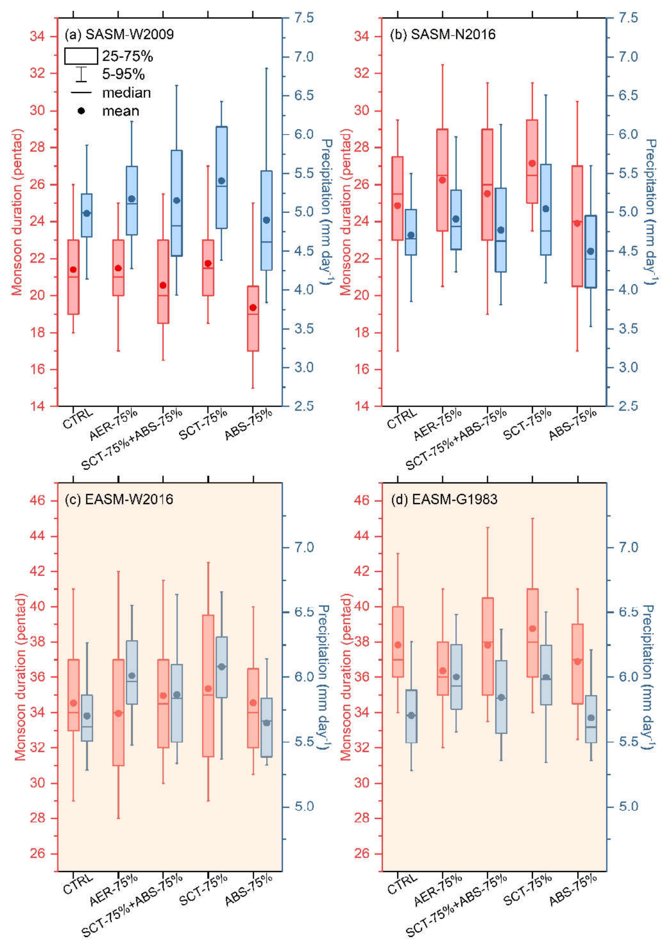

Figure 3: Box diagrams of the monsoon duration (red; unit: pentad) and precipitation (blue; unit: mm day^{-1}) over South Asia (a and b) and East Asia (c and d) in different simulations. Dots and middle horizontal lines inside boxes indicate mean and median values, respectively, and lower and upper sides of boxes indicate 25 and 75% range, respectively, and top and bottom line represent 5% and 95%, respectively. The boxes labelled SCT-75+ABS-75% in each panel are the linear addition of the impacts of the

reductions in the SCT and ABS. Panel (a) is derived based on the definition from Wang et al. (2009; hereafter referred to as W2009). Panel (b) is derived based on the definition from Noska and Misra (2016; hereafter referred to as N2016). Panel (c) is derived based on the definition from Wang, D. et al (2016; hereafter referred to as W2016). Panel (d) is derived based on the definition from Guo (1983; hereafter referred to as G1983).

Lines 271-286 (The comparison between the Fig. 3(a) and (b) and the relevant discussions. Note that the discussions involved the monsoon onset and withdrawal adjustments (Fig. 4; shown in the 17th Reply))

Note that using different definitions of monsoon onset/withdrawal dates may result in the variations in the monsoon duration response range although the SASM duration and precipitation adjustments in W2009 and N2016 are qualitatively consistent. The SASM durations in N2016 from different simulation sets are basically 4-5 pentads longer than those in W2009 (Fig. 3a and b). The SCT-driven extension of the SASM duration based on N2016 (2 pentads) is also longer than that in W2009 (0.4 pentads). The difference in the SASM duration adjustments between W2009 and N2016 can be attributed to the distinct selection of monsoon feature to characterize the monsoon subseasonal variations. Syroka et al (2004) pointed out that the withdrawal of the SASM defined by the precipitation is much later than that defined by the monsoon circulation due to the late decrease in precipitation in southern India. The precipitation continues to increase in southern Indian after September associated with the winter monsoon (Bhanu Kumar et al., 2004), while the SASM-related circulation characteristics becomes unclear in the meantime. Therefore, the SASM onset dates based on N2016 is roughly the same with those based on W2019, but the withdrawal date is about 5 pentads later, resulting in the longer monsoon duration (Fig. 4a and b). Moreover, there exists an additional enhancement of monsoon precipitation over SA in the “SCT” set, which further leads to the later SASM withdrawal and longer SASM duration in N2016 (Fig. 4b). Besides, the precipitation during early autumn is sensitive to the location and synoptic/sub-synoptic systems (tropical cyclones, depressions, easterly waves, north-south trough activity and coastal convergence, etc; Bhanu Kumar et al., 2004), which possibly contributes to the larger variation range in the monsoon withdrawal date in N2016.

Lines 305-308 (The comparison between the Fig. 3(c) and (d) and the relevant discussions. Note that the discussions involved the monsoon onset and withdrawal adjustments (Fig. 4; shown in the 17th Reply))

Compared to the EASM adjustments in W2016, the EASM show longer duration (about 3 pentads) in G1983 due to the later withdrawal (about 4 pentads). Zhu et al. (2012) has clarified that the climatological transition date of the zonal land-sea contrast in autumn over EASM-controlled region is about 3 pentads later than that of the monsoon circulation, which largely explained the relatively late monsoon withdrawal dates in G1983.

Lines 364-380 (The description about the linear addition of the impacts of the reductions in the SCT and ABS. Note that the discussions involved the spatial pattern of SASM and EASM responses (Fig. 5 and 6; shown in the 1st Reply))

Generally, the pattern of the anomalous precipitation and monsoon horizontal circulation over SA by adding the results of reducing SCT and ABS aerosols are similar to the results of reducing total aerosols, especially for the W2009 (Fig. 5). However, the precipitation north of 30°N shows a reduction in the validity of the linear addition assumption compared to the precipitation change in the simulation of reducing total aerosols, although most of the reduced precipitation does not pass the significance test ($p < 0.05$). There's also significantly increased precipitation over the southern part of SA in the linear addition, which is contributed by the impacts of SCT reduction. Additionally, an easterly anomaly appears over the Arabian Sea (10-20°N) in N2016 (Fig. 5f) as the linear addition of Fig. 5g and 5h, while an SASM westerly flow is enhanced over this region in the simulations of reducing total aerosols (Fig. 5e). The dominated impacts of SCT reduction and non-linear effects between the SCT and ABS contribute to the enhanced SASM westerly in Fig. 5e. The general feature of precipitation and circulation responses over the EA continent (north of 15°N) in the linear addition are also consistent with that in the simulation of simultaneous SCT and ABS reductions (Fig. 6), except for the insignificant decreased precipitation contributed by the impacts of ABS reduction (Fig. 6b and 6f). For the quantitative results of regional precipitation adjustments, the linear addition results show an increased precipitation in both SA and EA compared with the CTRL results (Fig. 3). The increased precipitation amount is less than the results of reducing total aerosols due to the simple addition of precipitation change caused by ABS reduction. However, the results of linear addition are inconsistent with the total aerosol reduction results in terms of the SASM and EASM duration variations, indicating that the impacts of reducing SCT or ABS alone on monsoon subseasonal variability cannot be simply added up.

17. Figure 6, similar as Figure 3, could you change scale of panel b from day to pentad for better comparison and consistency?

≫ Figure 6:

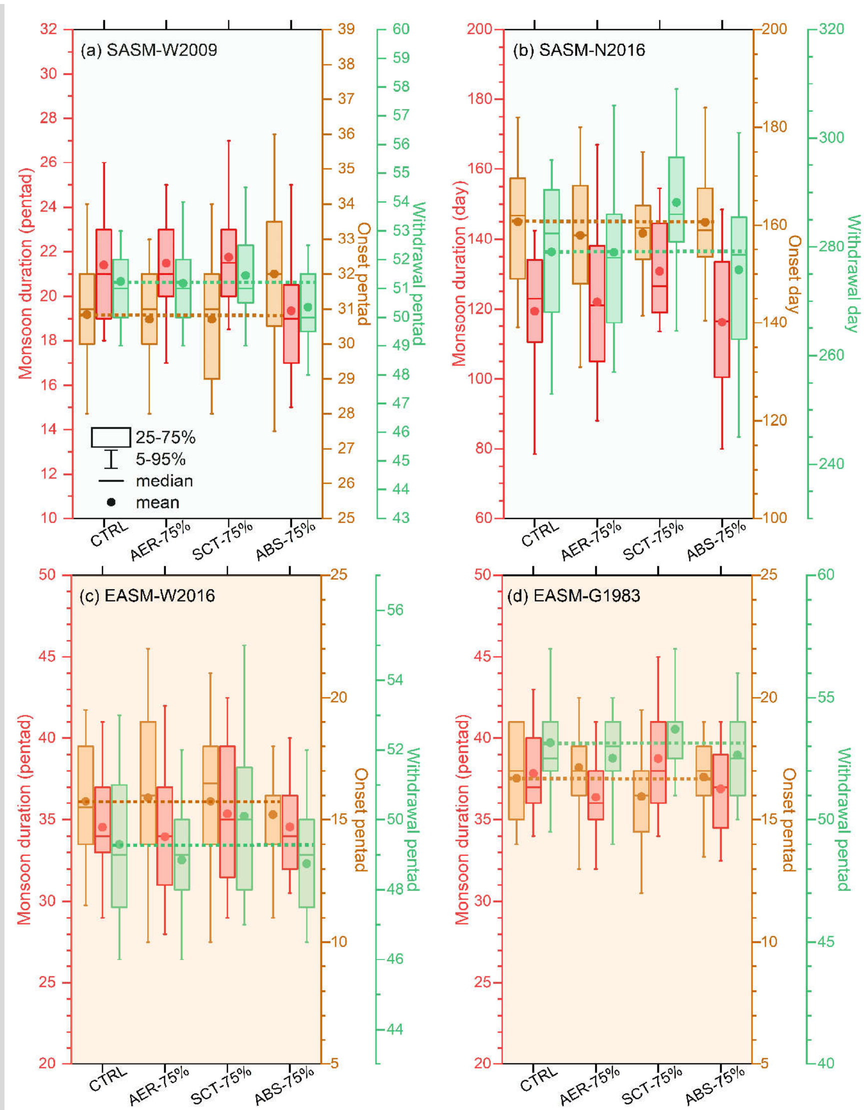

Figure 6: Same as Figure 3, but for the monsoon onset dates (yellow; unit: pentad for a, c and d, day for b), withdrawal dates (green; unit: pentad for a, c and d, day for b) and duration (red; unit: pentad for a, c and d, day for b).

Thank you for this valuable suggestion. In the revised manuscript, the serial number of Fig. 6 is changed to Fig. 4. The scale for left y-axis of Fig. 4(b) has been changed from day to pentad. The linear addition of the impacts of the reductions in the SCT and ABS has also been added in Fig. 4. **The comparison between the Fig. 4(a) and (b), the com-**

parison between the Fig. 4(c) and (d) and the relevant discussions have been added in Lines 271-286 and Lines 305-308, which can be seen in the 16th Reply.

Lines 999-1002 (Fig. 4)

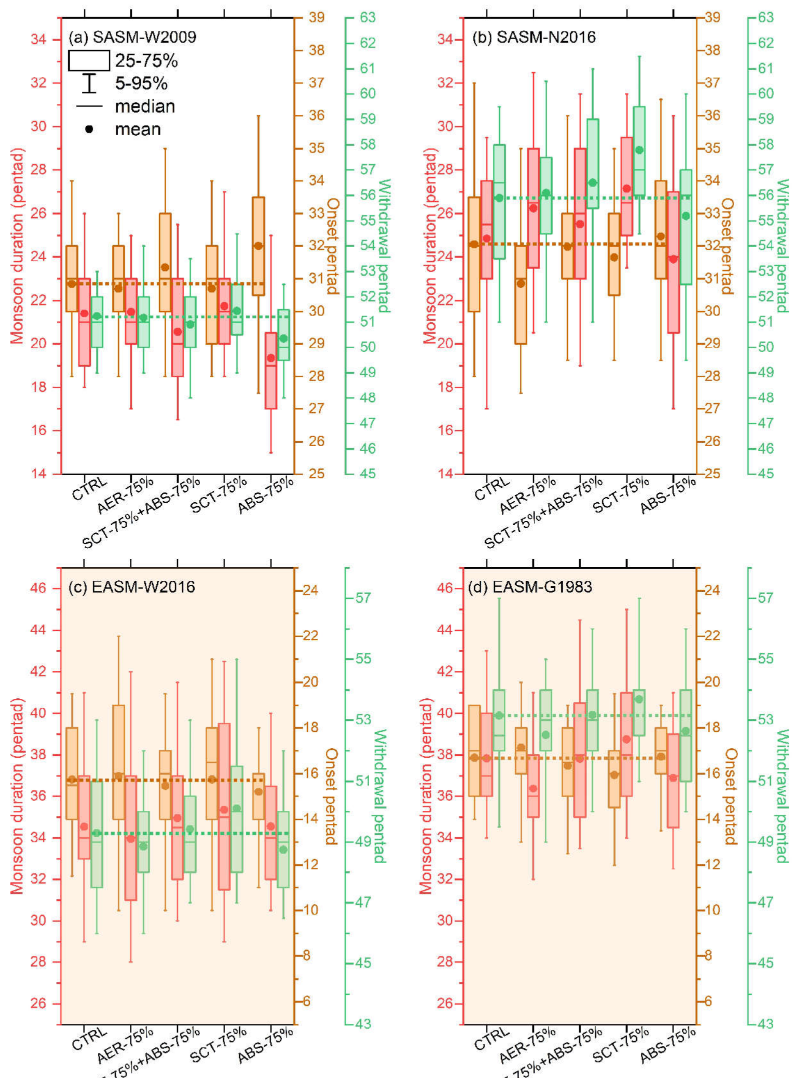

Figure 4: Same as Figure 3, but for the monsoon onset dates (yellow; unit: pentad), withdrawal dates (green; unit: pentad) and duration (red; unit: pentad). The yellow and green dashed lines denote the mean values of monsoon onset and withdrawal in the CTRL simulation set, respectively.