Response to reviewer 1

Format of responses: (1) comments from referees/public, (2) author's response, and (3) author's changes in the manuscript.

General comments:

(1) The paper is well written, starting with a good presentation of methods data and cases. Results are clearly presented with a fluent language and well-designed figures. I have two general comments, that will recur in the specific comments below:
a) authors need to be clear that their “aerosol forcing” emulates absorbing aerosols only, not scattering aerosols. This should be evident if not in the title, then at least in the abstract and throughout the text.
b) the authors present many good figures, but there is a general lack of quantification and statistics.
(2) We thank the reviewer for their comments and for taking the time to review the manuscript. We have now clarified that we are primarily concerned with the emulation of absorbing aerosols and their effects on the Asian monsoons. Furthermore, we have improved the statistical analysis of our results (details below).
(3) Various instances in the text have been updated to specifically refer to absorbing aerosols. Figures have been updated with stippling to show statistically significant changes. These are determined as where the anomaly (e.g. 60W/m^2 forcing – control) is greater than 2 times the interannual variability of the June-July-August mean, with respect to the reference simulation (e.g. 60W/m^2 forcing). In conjunction, the text has edited to include discussion of the statistical relevance of the anomaly signals. Example of figures with added stippling can be seen in response to some of the comments below.

Specific comments:

(1) P2: both in terms of the response of the monsoons and in the future climate forcing.
Could you please consider rewording this sentence as it’s a bit confusing. How the monsoon evolves in a changing climate is uncertain because we don’t know enough about the how the monsoon reacts to a forcing. We also don’t know exactly how the future forcing of the climate will be. Was that the point?
(2) Yes – firstly, that response of the monsoon to a forcing is uncertain, and secondly that the nature of the forcing itself is uncertain. Reworded sentence to clarify.
(3) “There remains considerable uncertainty in how the monsoons will evolve in a changing climate, both in terms of the response of the monsoons to an applied forcing and in the nature of the future climate forcing itself.”

(1) P2: The multi-model mean usually performs better than any single model [14–17]. Does this have some physical explanation or is it just pure luck?
(2) The use of multi-model ensembles is widespread and it is often assumed or found that the multi-model average performs better than any model. The argument is that by averaging over different models, structural uncertainty is partly taken care of (Tebaldi and Knutti, 2007: https://royalsocietypublishing.org/doi/10.1098/rsta.2007.2076). However, as one of the authors has discussed in Ghil and Lucarini, 2020 (https://doi.org/10.1103/RevModPhys.92.035002), this is far from being a scientifically error-proof approach. What one can say, instead, is that the use of multiple models allows for a wider spread than a single-model ensemble, hence more thoroughly sampling model error. It is really not the goal of this paper to dwell on this topic, despite the evident importance.
(3) No changes implemented.

(1) P3: Generally, aerosols have a stabilising effect on the atmosphere, through surface cooling and mid- tropospheric warming, increasing the stratification of the atmosphere and causing a drying trend [35–37]
This is indeed an important effect, but I disagree that is a *general* effect. This is an example of places in the text where the fact that authors are focusing on absorbing aerosols needs to be made clear.
(2) We have removed "mid-tropospheric warming" so that the sentence can refer to aerosols in general, with the following paragraph going into more detail regarding absorbing and scattering aerosols and their specific effects.
(3) "Generally, aerosols have a stabilising effect on the atmosphere, through surface cooling, increasing the stratification of the atmosphere and causing a drying trend which results in a weaker monsoon (Li et al., 2016; Wilcox et al., 2020; Ayantika et al., 2021; Cao et al., 2022)."

(1) P3: but moving forward, greenhouse gas forcing is expected to dominate, which is associated with a likely increase in monsoonal rainfall in the northern hemisphere
I agree that aerosols have played a stronger role historically than they will in the future. However, in the near- term we may see quite strong aerosol trends (reductions, presumably, but still) in certain regions. In the longer terms, greenhouse gases will indeed dominate, but I think the authors should consider adding the point that aerosols are still important in the near-term (also elevating the importance of your analyses).
(2) Added an extra sentence concerning importance of aerosols on the Asian monsoons in the near-future. Of course, considerable uncertainties remain with regards to future technological development and implementation (or not) of air quality policies.
(3) "Historically, aerosol forcing has dominated, linked with a declining rainfall trend over the latter half of 20th century (Bollasina et al., 2011; Polson et al., 2014; Li et al., 2015; Undorf et al., 2018; Dong et al., 2019), but moving forward, greenhouse gas forcing is expected to dominate, which is associated with a likely increase in monsoonal rainfall in the northern hemisphere (Monerie et al., 2022). In the near-term, fluctuations of aerosol concentrations in the Asian region will continue to impact the monsoons, with increases in anthropogenic emissions acting to weaken the large-scale circulation and hydrological cycle, thus weakening the monsoons, whilst decreases in emissions, perhaps from air quality policies, will likely intensify the monsoons."

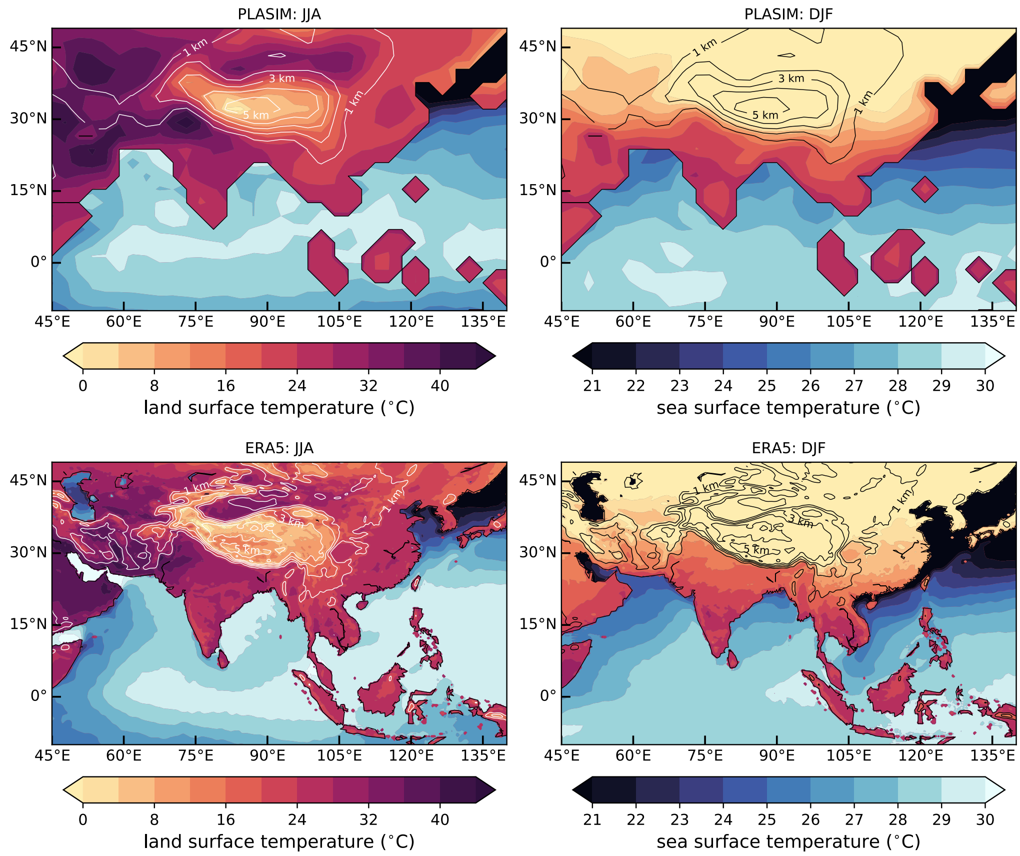
(1) P4: The main goal is to understand the impact of aerosol forcing on the
Please add "absorbing" before "aerosols".
(2) We agree with the reviewer that this needs to be made clearer.
(3) Changed various instances of "aerosols" to "absorbing aerosols".

(1) P6: Here, we use a combination of our own simulations with the PLASIM model and results from existing literature that use a hierarchy of models to quantify the responses of the South and East Asian monsoons to a range of future climate scenarios.
It is not entirely clear what is meant here: are results from other studies used in this study? If you just refer to other studies in the text it would be good to reword this sentence so it doesn't seem like they are a direct part of this study.
(2) Re-worded to make clear that we are using results from a single model, with comparisons to other studies in the text.
(3) "We use the intermediate complexity model, PLASIM, to quantify the responses of the South and East Asian monsoons to a range of future climate scenarios, thereby contributing to the existing literature and ensuring that a hierarchy of models are represented."

(1) P7: Figures1–4 show the performance of a 50-year control simulation with the PLASIM model
I usually think of a model's performance as how the model does compared to the real world (i.e., compared to observations). I realize that you show and explain how the model does display real-world features, but section 2.1 in general lacks the observation element. It is obvious that the authors know their field and the description of the PLASIM features in the text is excellent, but the reader needs to be shown – not just told, without any references – that it agrees with observations. Adding references to the literature when describing different dynamical features, as well as a figure or two comparing PLASIM directly with observations is needed here.

(2) We agree with the reviewer that this should have been discussed in greater detail. Comparison to observations was done at an early stage but not all figures/analysis were included in the manuscript due to concerns over length. Given the idealistic nature of the experiments, extensive quantification of performance against, for example, satellite data, isn't applicable. Our requirements are that PLASIM reproduces the large-scale features of the monsoons, with a clear seasonal cycle, which is hopefully now evident.

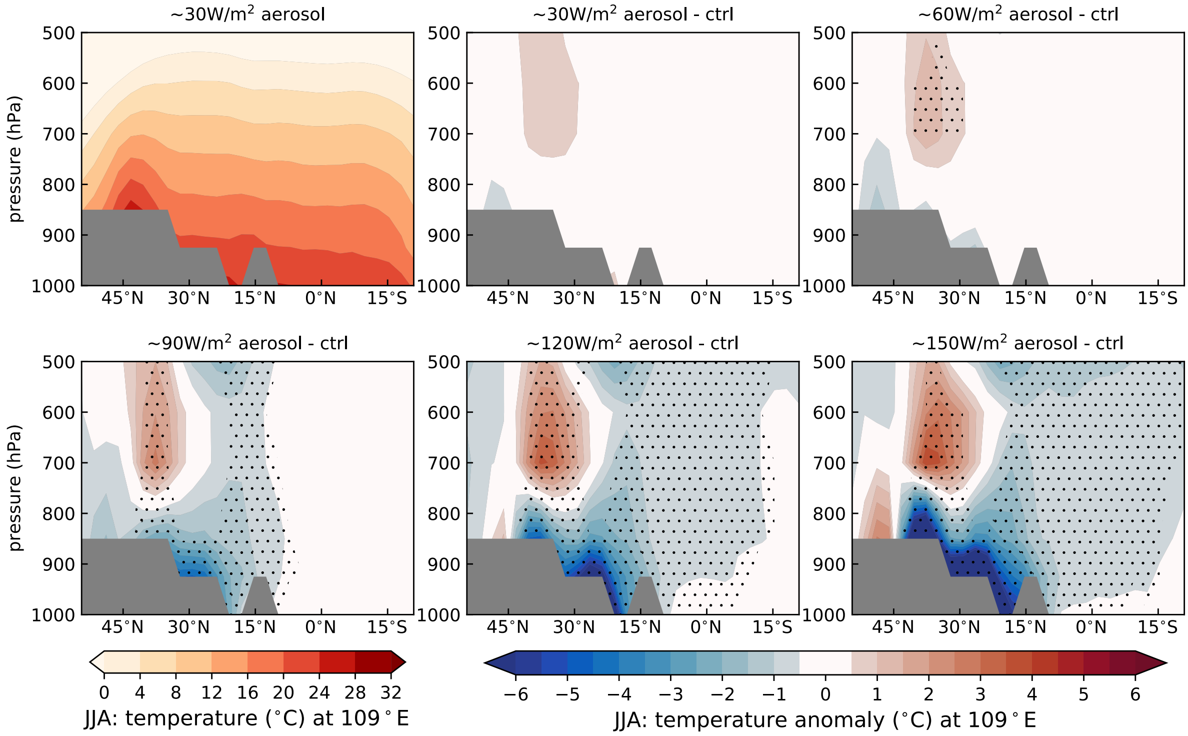
(3) We have added subplots to Figures 1-4 to show the equivalent variables from ERA5 reanalysis data, to allow for visual comparison with the PLASIM model. Updated *"Section 1.2 Model Validation"* to reference and discuss the updated figures. Example of revised Figure 1 below.



(1) P10: The added aerosol forcing causes the surface to cool
It would be very interesting to see a regional average of the vertical temperature profile, to see how it changes with this "aerosol forcing".

(2) Figure 8 shows the area-averaged surface temperature against aerosol forcing, and Figures S1 & S4 show the surface & 700 hPa contours for aerosol-only and aerosol-with-2xCO_2 forcing. Additionally, we will add latitudinal and longitudinal cross-sectional figures to show the vertical temperature profile changes with aerosol forcing.

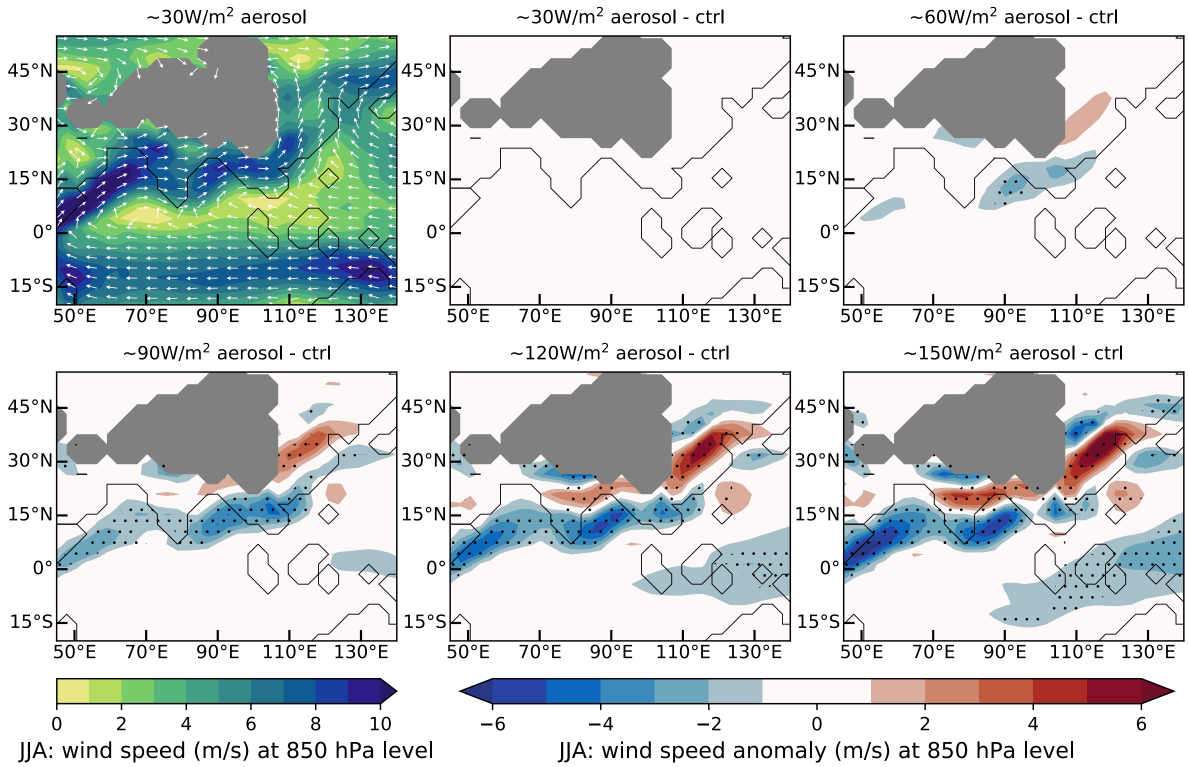
(3) Example of a section at 109°E. Aerosol forcing is added approximately between 550 & 750 hPa, corresponding to the warm (red) temperature anomaly at 40-25°N. Surface cooling (blue) is also evident in the same region.



(1) Figure 7, arrow sizes: In the figures with wind arrows, it is extremely difficult to see the direction of the arrows. Would it be possible to play with the plotting here, trying e.g. to make the arrowheads larger, to have fewer but larger arrows, or something like that?

(2) It is an ongoing challenge to find the right balance between size, colour and density of the vectors (arrows). We have tried to improve on this, as summarised and shown below.

(3) Reduced number of arrows & made arrowheads larger (example figure 7a below).



(1) Figure 7, arrow directions and wind speed anomalies: I'm having difficult with these winds, and I would like to underline that if there is a well established consensus that this is how wind changes are displayed, then the following comment may be disregarded: Authors have chosen to show anomalies in both wind speed and in wind direction. I'm not sure this is the best way to convey the results, and to show how the climate of the region looks under a strong aerosol-like perturbation. For instance, looking at the 850hPa panel for ~150W/m2, there is a strong blue band stretching across south India and towards the southwest. This dark blue color should be read as: the SW monsoon wind has weakened dramatically and is close to zero. This, to me, is very counter intuitive. Also, when arrows point in the opposite direction, this does not necessarily signify that the average wind direction has turned? It would be easier to interpret the changes if maps showed absolute wind speeds and directions, so they could be compared directly to the first green maps. Lighter/darker colors than that "baseline" map would mean stronger/weaker winds, and arrows would point in actual wind directions.

(2) As above, it is difficult to strike the right balance when displaying vectors, particularly as visual aspects are subjective. Following the reviewers comment, the arrows on the anomaly plots have been removed so as to focus on the changes in wind speed. Representation of the arrows on the forcing (i.e. not anomaly) plots have been improved as per previous comment.

(3) Removed arrows on wind anomaly plots for clarity, as per example figure above.

(1) P13: There is a strengthening of the low-level southwesterly wind in East China, causing dry air to be advected towards East Siberia

I'm probably misreading this but: a stronger wind from southwest sends dry wind towards the west?

(2) A southwesterly wind refers to a wind coming from the southwest and travelling towards the northeast. Edited the relevant sentence in the manuscript to clarify.

(3) "There is a strengthening of the low-level wind in East China (20-40°N), causing more dry air to be advected from southwest to northeast, towards Eastern Siberia, and corresponding to a reduction of precipitation in the region."

(1) P14: We note again that between 0 and 60 W/m2 forcing, although the convective precipitation is gradually reducing, the precipitable water does not correspondingly decline.
Why was that?
(2) There is an explanatory sentence in the previous section: "Therefore, the decline in rainfall is primarily attributed to a reduction in precipitation efficiency, which is due to the increase in the static stability of the lower levels of the atmosphere, as opposed to a scarcity of moisture availability." However, the explanation bears repeating in later sections where necessary.
(3) Added an extra sentence: "This is attributed to a reduction in the precipitation efficiency."

(1) P15: A more quantitative angle (Figure 8)
This paragraph is one place where I believe the authors could have been more quantitative in their analyses. Could you try to put a quantitative number on the "sensitivity to aerosol forcing", for instance? The numbers would be contrasting nicely between convective precip. and precipitable water.
(2) We agree with the reviewer. We have added explicit reference to the sensitivity of convective/large-scale precipitation, precipitable water and surface temperature, to the aerosol radiative forcing in the linear range 0-60 W/m^2, and (approximately linear) range 60-80 W/m^2. The text in this section already discusses the changes in gradient before and after 60 W/m^2, but now we quantify this using the table below, which gives the slopes of the regions/variables following Figure 8.
(3) We have added a table for each simulation to provide quantitative information in support of the text – example of table for *aerosol only* simulation below.

Table 1: Slopes for Figure 8, taken as a linear fit for the ranges 0-60 and 60-80 W/m^2 absorbing aerosol forcing, for aerosol only *simulation.*

	Convective precipitation (mm/day per W/m^2)		**Large-scale precipitation (mm/day per W/m^2)**		**Precipitable water (kg/m^2 per W/m^2)**		**Surface temperature (°C per W/m^2)**	
Forcing range (W/m^2)	**0-60**	**60-80**	**0-60**	**60-80**	**0-60**	**60-80**	**0-60**	**60-80**
North India	-0.019	-0.054	0.005	0.008	0.008	-0.078	-0.060	-0.069
South India	-0.001	-0.008	0.009	0.007	0.009	-0.027	-0.032	-0.042
East China	-0.058	-0.115	0.008	0.008	0.005	-0.154	-0.024	-0.103
Southeast Asia	-0.068	-0.063	0.006	0.023	-0.030	-0.086	-0.017	-0.117

P15: Regarding the analysis of forcing vs regional climate impact (Section 3.2): it would be good to see a few concluding sentences reminding the reader why these results are relevant – what are their link to the real world (small/large emission changes)?
(2) We agree with the reviewer that it is important to discuss the relevance of the results. But we believe that sufficient discussion is already presented in the Introduction and in the Conclusions. A sentence has been added in Section 3.2 to highlight the relevance of the results.
(3) "East China shows the highest sensitivity to absorbing aerosol forcing of approximately 60W/m^2, where the convective precipitation drops to almost zero; essentially a breakdown of the monsoon

system. In terms of future climate scenarios, the aerosol forcing over East China is key for determining the precipitation response, both locally and remotely."

P16: Although the precipitable water is considerably greater when carbon dioxide levels are doubled Provide the reader with a quick explanation of why that is.

(2) The explanation is given the sentence below. Additionally, we add a reference to Held and Soden, 2006 (https://doi.org/10.1175/JCLI3990.1).

(3) "Given the warmer surface temperatures in the *aerosol with 2xCO_2* simulation, we would expect to see greater atmospheric moisture content and higher rates of evaporation and precipitation, compared to the *aerosol only* simulation. Although the precipitable water is considerably greater when carbon dioxide levels are doubled…"

P17: noting that the elevated levels of precipitable water do not correspond to comparable increases in precipitation

Please provide a physical explanation to this.

(2) As per previous comment for P14: the decline is precipitation is due to a reduction in the precipitation efficiency, which results from increased static stability of the lower troposphere. Edited the relevant sentence to add explicit reference to convective precipitation and static stability, as below.

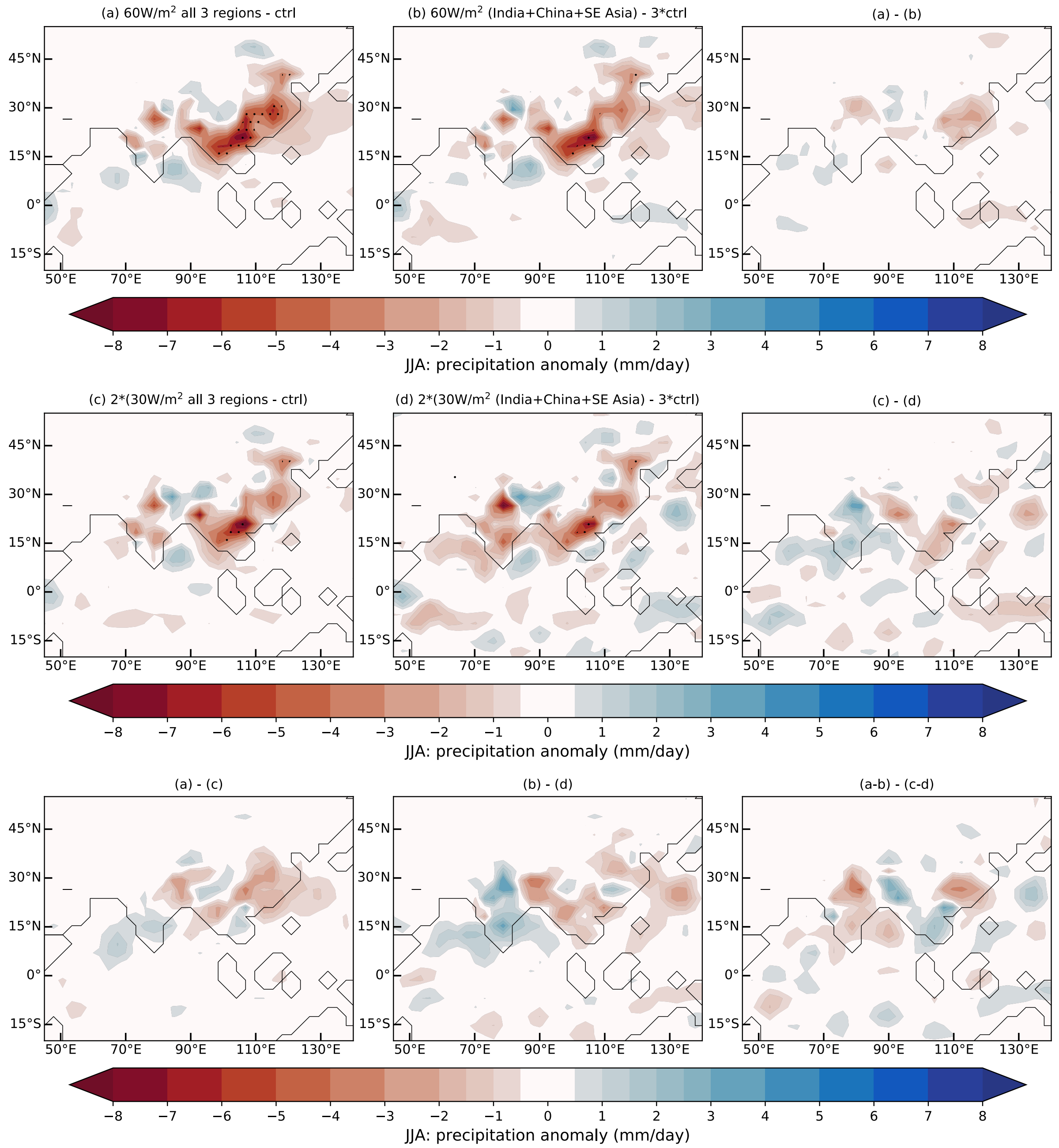
(3) "Once again, we highlight the discrepancy between the precipitable water and the precipitation, noting that the elevated levels of precipitable water do not correspond to comparable increases in convective precipitation, due to a reduction in the convective precipitation efficiency and the corresponding increase in static stability of the lower troposphere."

P17: Considering Figures 9 & 10, there is little difference in the three columns, which represent approximate forcings of 30W/m2, 60W/m2 and 90W/m2. This indicates a fairly linear behaviour These linearities must be quantified. Spatial correlations between the maps are one suggestions, but I'm sure there are other.

(2) The linearity between the intensity of the forcing and the response to key variables (precipitation, precipitable water & surface temperature) is considered in Figure 8 and Section 3.1. Although linearity in the response is evident from Figure 8 & earlier figures, the focus in Section 3.1 is on identifying regime transitions under extreme forcing. From Figure 8, the response to forcing in the range 0-60W/m^2 is reasonably linear; thereafter, we observe changes in the response relative to the applied forcing.

The linearity of the response to area of applied forcing is considered in Section 5.1, with Figure 12 showing the spatial fields. This section has been edited to include results from aerosol forcing of intensity 30W/m^2, as well 60W/m^2.

(3) Edited text and updated figures (see below) in Section 5.1 to show linearity of the response to forcing at 30W/m^2 and 60W/m^2. Stippling has been added where the anomaly is greater than 2 times the interannual variability with respect to the control run. By the right column, there are no significant differences in the precipitation response to forcing regions simultaneously or forcing regions independently and combining, indicating linearity in the response. Similarly, the bottom row indicates linear behaviour in the response to the intensity of forcing, 30 vs 60W/m^2.



P17: Our results suggest that in the future, the anticipated reduction in aerosol concentration may have a greater impact on monsoonal precipitation than the increase in greenhouse gases.
This is a nice and clear result, written in a way that conveys the relevance of this study. This message should be underlined – in the abstract and/or in the final conclusion.

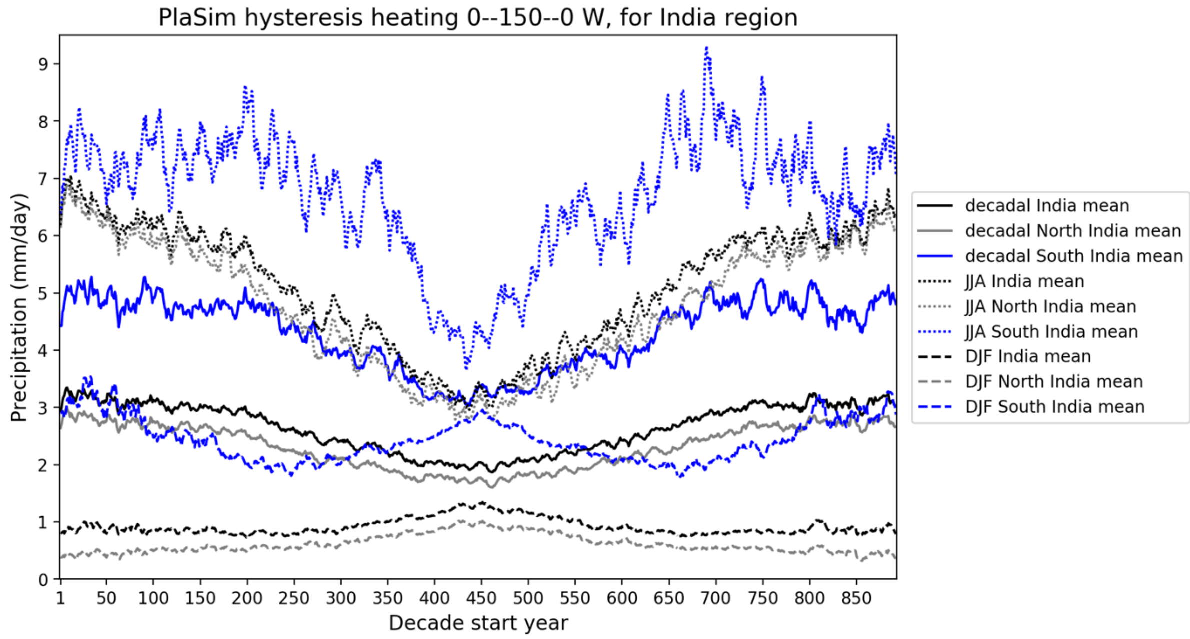
(2) We agree that this is an interesting result. We don't want to overstate it because it has been obtained in a rather simplified model setting. Having established some interesting results with an intermediate complexity climate model, we believe is it worth pursuing the research using more comprehensive modelling tools.

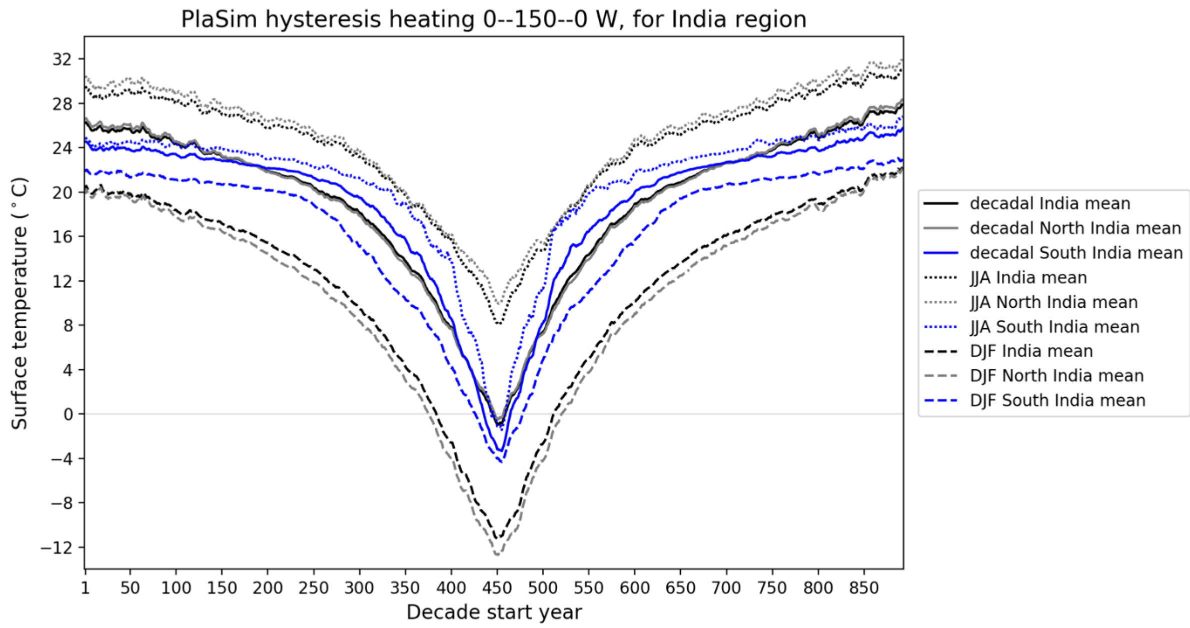
(3) Added sentences to the Abstract ("These results suggest that in the future, the anticipated reduction in aerosol concentration may have a greater impact on monsoonal precipitation than the increase in greenhouse gases.") and Conclusions ("We find that the precipitation response is more sensitive to absorbing aerosol than greenhouse gas forcing, highlighting the importance of air quality policies and the impact they can have on the future state of the South and East Asian monsoons.") regarding the importance of aerosol vs greenhouse gas forcing. Also added another sentence to the

Conclusions to highlight the limitations of our study, and our future work aims: “Our results are limited by the low resolution and lack of explicit aerosol interactions and chemistry, but future work will aim to address these issues by repeating similar experiments using a more complex global climate model.”

P18: The precipitation response of India to forcing applied over East China is nearly as strong as when the forcing is applied locally, albeit with opposing trends.
Again, please provide a physical explanation, or at least a suggestion to one.
(2) The fact that the presence of an aerosol forcing over East China leads to an increase of precipitation over Northern India is an interesting phenomenon. Partly comparable results had been found in Herbert et al. 2022. Understanding this processes is highly nontrivial and we are collaborating with the Herbert et al. team exactly to discover the mechanisms in action.
(3) “The precipitation response of India to forcing applied over East China is nearly as strong as when the forcing is applied locally, albeit with opposing trends. Similar asymmetry in the teleconnection between East China and India in relation to local absorbing aerosol forcing has been shown in Herbert et al. (2022); however, further is required to fully understand the underlying mechanisms.”

P20: On removal of the aerosol forcing, we find that the monsoon system recovers fully, indicating that there is no hysteresis in our model simulations.
Where is this shown? The reader needs to see this finding.
(2) Our model is, by construction, rather weak in representing long climatic time scales, given the lack of an active ocean featuring slow dynamics. We add a figure below for the interest of the reviewer, showing the decadal mean precipitation and surface temperature over the length of the simulation (900 years). The start and end years correspond to 0 W/m^2 absorbing aerosol forcing, whilst the middle year (450) corresponds to 150 W/m^2 absorbing aerosol forcing.
(3) No changes implemented.





(1) Conclusion: Given the tool used, I believe the method of emulating absorbing aerosols is as good as any. However, it would be good to see a short discussion of caveats connected to the very idealized nature of this type of perturbation.

(2) We agree with the reviewer that this is an important point, which we have discussed in detail in Section 2.2. We have also added a sentence to the Conclusions (see below).

(3) As per reviewer comment for P17, added a sentence to the Conclusions: "Our results are limited by the low resolution and lack of explicit aerosol interactions and chemistry, but future work will aim to address these issues by repeating similar experiments using a more complex global climate model."

Technical corrections:

(1) Line numbers on the document will greatly ease the reviewer job in the next round!

(2) Sorry - there are line numbers on the submitted article (.pdf) to Earth System Dynamics, but not on the preprint, which was originally posted on Research Square and uses a slightly different template.

(3) Line numbers shown in revised manuscript.

(1) First sentence of introduction: “region economy” -> “region’s economy”

(2) Edited.

(3) “The South and East Asian monsoon systems are of key importance for the region's economy, agriculture and industry.”

(1) P14: a little bug: ¡60W/m2

(2) Latex encoding error.

(3) “At low (<60W/m^2) aerosol forcing”

(1) P14: form -> from: form 0 to 150W/m2

(2) Edited.

(3) “As the radiative forcing is increased from 0 to 150W/m^2”

(1) P14: sdepends -> depends: with 2xCO2andaerosol only, sdepends

(2) Already edited in submitted version.

(3) “*aerosol with 2x*CO_2 and *aerosol only*, depends only”