Response to reviewer 2

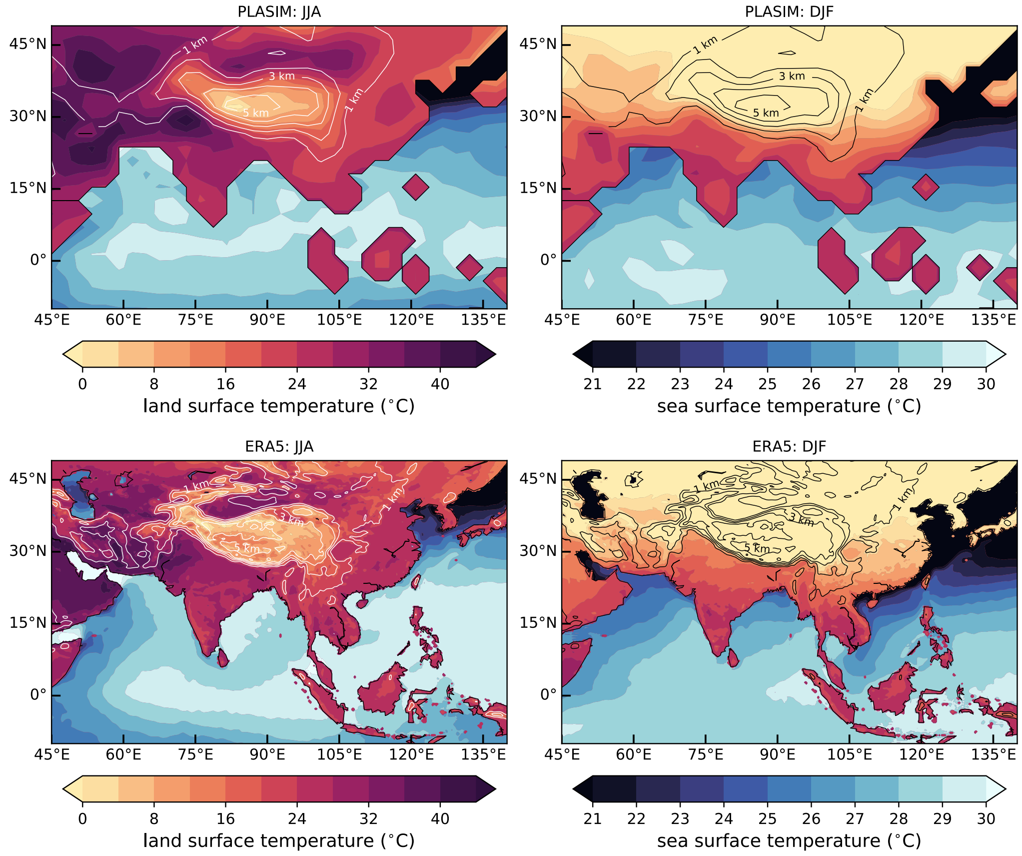
Format of responses: (1) comments from referees/public, (2) author's response, and (3) author's changes in the manuscript.

Specific comments:

(1) Model evaluation against the observations is missing in the manuscript. Some meteorological parameters like precipitation, winds, and surface temperature as shown are needed to be validated against the observations.

(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) The values selected for aerosol forcings are too high. The values ranging from 30 to 40 W m^{-2}are valid over a local region and season depending upon the emission type but applying all over India or eastern China could have an overestimation of aerosol effects. What is the rational thinking behind increasing aerosol forcing to 150 Wm^{-2}? If there is no interactive chemistry component in the model then these are highly idealized simulations. I suggest making it clear in the title.

(2) We have included additional figures for 30W/m^2 forcing as well as the 60W/m^2 forcing, to help quantify the linearity. Nonetheless, we remark that locally, in heavily polluted urban conglomerate and industrial regions, forcings of around 100 W/m^2 have been observed – see references in Section 2.2. In particular, see Table 2 in Kumar and Devara (2012), where values of -46 to -110/+46 to 115 W/m^2 are quoted for surface/atmosphere forcing in Delhi. As mentioned in the manuscript, the point of including unrealistically high forcings is to cover a parametric range of forcings. In particular, to see the behaviour leading up to a breakdown or severe weakening of the monsoon systems. The title mentions "an intermediate complexity climate model", and states that we are modelling the *effect* of absorbing aerosol forcing rather than explicitly adding aerosols. It is mentioned in Section 2.2 Experiment design that "The PLASIM model has no explicit treatment of aerosol interactions".
(3) We have added Figures in Section 5.1 to include results from simulations with an absorbing aerosol forcing of 30 W/m^2.

(1) I assume these values 30 to 150 Wm^{-2} depict the aerosol atmospheric forcings (Top of the atmosphere (TOA) – surface) right? then why only it is applied to 550-750 hPa? Please clarify.
(2) We are mostly considering the case of absorbing aerosols. To a first approximation, the net energetic impact on the atmosphere column (top of atmosphere - surface) is zero. A heating of varying intensity, say H, is applied over 3 model levels which roughly correspond to 550-750 hPa (mid-troposphere). Thus, each of the 3 model levels has an applied forcing of intensity H/3. At the same time, a cooling of intensity -H is applied at the surface, because less solar radiation reaches the surface. This is now further clarified in the text.
(3) Added sentences in Section 2.2 to clarify that heating of intensity H/3 is applied at 3 mid-tropospheric levels, and also a cooling of intensity -H is applied at the surface.

(1) It is a bit confusing that if the mid-tropospheric heating is applied then the monsoon circulation at 850 hPa should have strengthened over India and southern China. In general, it should have created a mid-tropospheric temperature gradient but I see a consistent decrease in the precipitation. Please clarify.
(2) As mentioned above, the aerosol forcing consists of both a mid-tropospheric heating and a compensating surface cooling, such that the net change in the atmospheric column is zero. The absorbing aerosol forcing has a stabilising effect, increasing the stratification of the atmosphere and leading to reduced (convective) precipitation and weakening circulation (e.g. Li et al. (2016); Wilcox et al. (2020); Ayantika et al. (2021); Cao et al. (2022) – see manuscript for full references).
(3) No changes implemented.

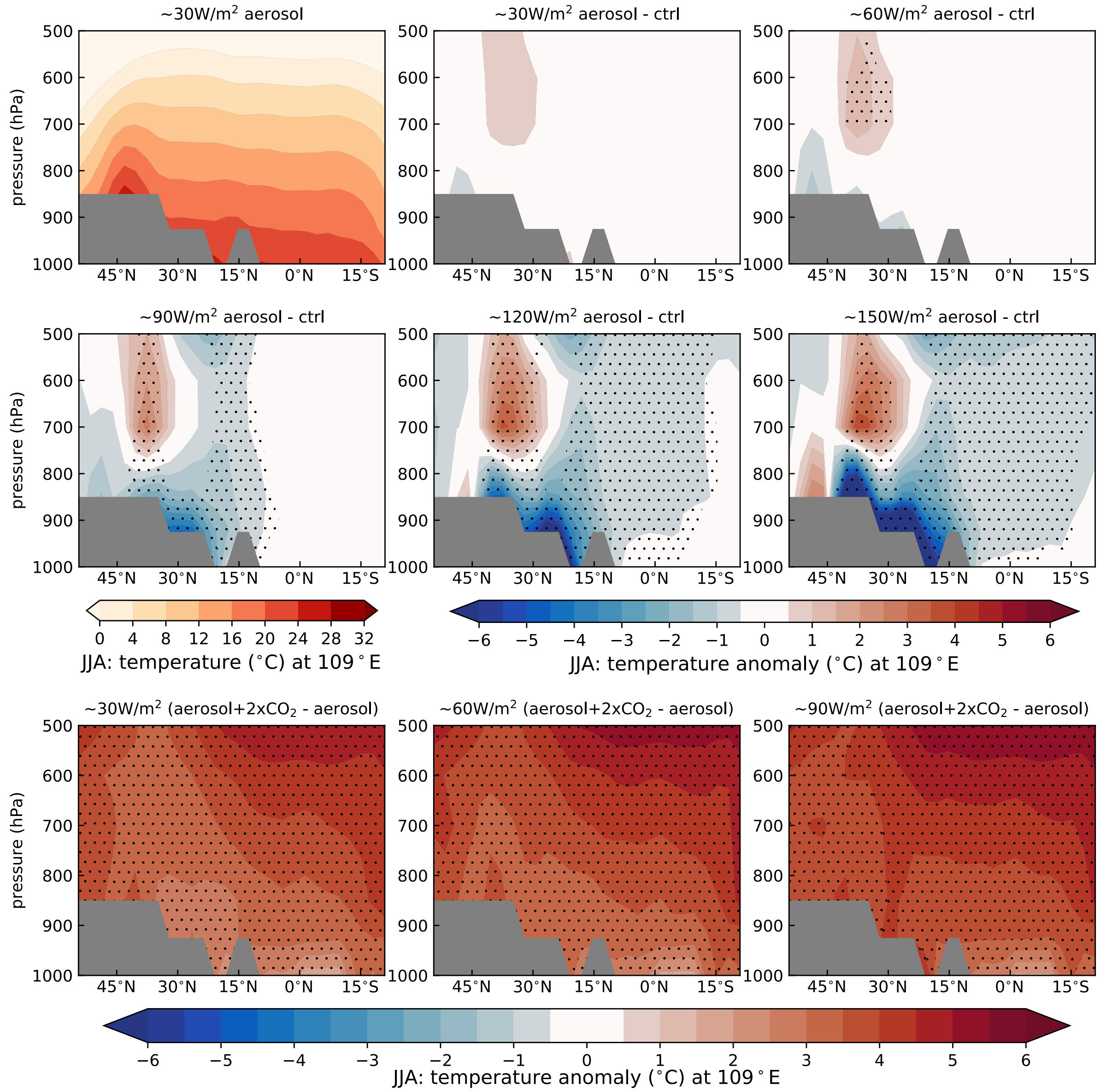
(1) Could you please include some discussion on why there is an increase in precipitation over north India in 120 to 150 Wm^{-2} aerosols forcing?
(2) As discussed in the text (Section 5), the overall effect of applying aerosol forcing over India is smaller than what is realised in the two other regions because aerosol forcing over East China leads to increasing precipitation over Northern India, thus countering the effect of the local forcing and making it non-statistically significant even for very strong forcing.
(3) Figures have been updated to show stippling where the anomaly is greater than 2x interannual variability: there is no stippling over North India so the increase in precipitation is much less significant than the reduction in precipitation across South India, Northeast India, East China & Southeast Asia.

(1) The responses in monsoon precipitation obtained in this paper could be possibly due to large amounts of scattering aerosols (anthropogenic sulfates) which seems consistent with the earlier published literature. Here, through absorbing aerosol forcings, a similar effect is obtained. Why? I am not sure whether the dynamics are correctly responding to aerosol forcing.

(2) We see a reduction in precipitation, a surface cooling and a weakening of the circulation, primarily in the regions where the absorbing aerosol forcing is applied. Thus, these results are consistent with published literature – see Section 1 for references. Some effects on the monsoons, such as surface cooling and a reduction in moisture availability, are common to both absorbing and scattering aerosols. Further work aims to isolate the specific effects of scattering aerosols, as opposed to absorbing aerosols, on the Asian monsoons, in a similar way to Herbert et al. 2022.
(3) No changes implemented.

(1) Whether the surface temperature anomalies or the tropospheric temperature anomalies induced by aerosol/2xCO_2 forcings are more sensitive in driving monsoon precipitation should be pointed out.
(2) The applied forcings affect both the surface temperature and the mid-troposphere. We do not see a strong reason to separate the effect of the two anomalies, as we are focusing on the forcing itself. In the case of the aerosol forcing, the surface and the mid-tropospheric anomalies both contribute to increasing the static stability of the atmosphere, thus decreasing the convective precipitation.
(3) No changes implemented.

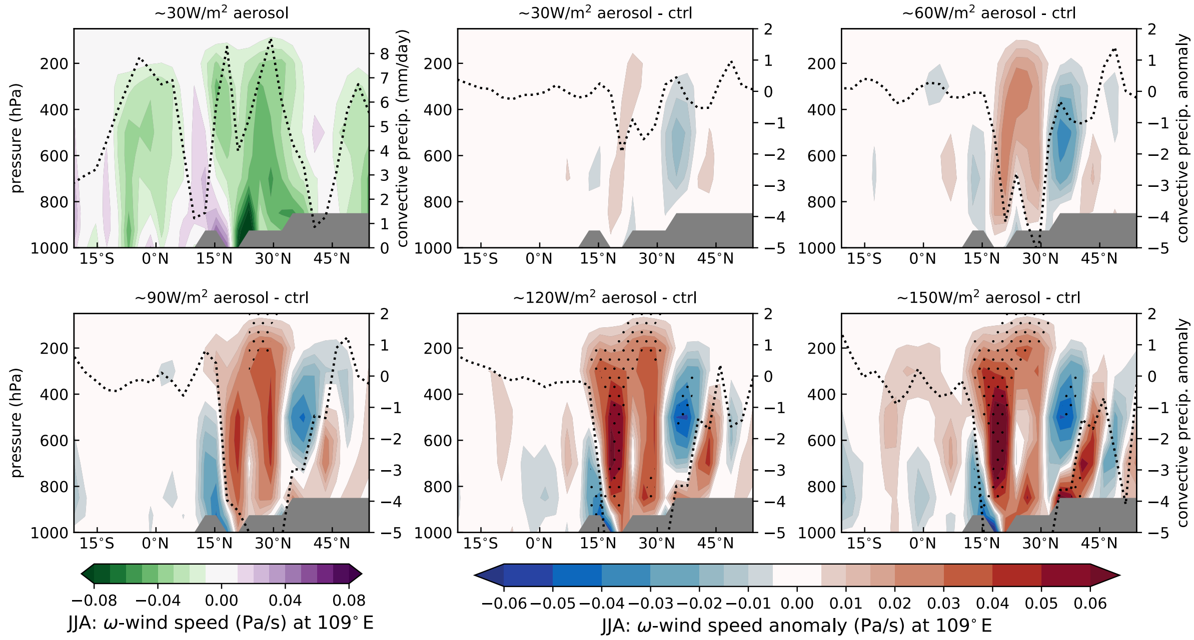
(1) It would be nice to check the latitudinal cross-section of changes in air temperature vertically due to aerosol forcings. Subsequently, then while including 2xCO_2 forcings.
(2) We agree with the reviewer. Sections at 20°N and 109°E have been added to show the vertical temperature profile under absorbing aerosol forcing, with stippling to show statistically significant changes. Over the regions of applied forcing, a warm temperature anomaly can be seen around 500-850 hPa, and a cool temperature anomaly close to the land-surface. Similarly to Supplementary Figure S4, the *aerosol with 2xCO_2* simulation shows warmer temperatures, particularly at mid-levels, than the *aerosol* only simulation.
(3) Added figures for a longitudinal & a latitudinal cross section of temperature. Example below.



(1) Inspection of vertical velocity responses to aerosol and 2xCO_2 forcings could be useful. Please check.

(2) We agree that this is a useful diagnostic, although convective precipitation is the meteorological field of greatest interest for us. We are including additional figures and analysis to include vertical velocity responses.

(3) Added extra figures of vertical velocity (omega) and updated the text to include analysis of added figures. Example vertical cross section of vertical velocity at 109°E shown below, with the dotted line showing convective precipitation. One can clearly see a strong reduction of convective motion and corresponding reduction of convective precipitation.



(1) "The intense surface cooling is primarily responsible for activating the ice-albedo effect.." on page 10. How does the ice-albedo affect the vertical distribution of temperature?

(2) As the surface temperatures cool to the extent that oceans begin to freeze, the increasing area of sea ice and snow cover leads to a higher albedo, thus increasing the amount of incoming radiation being reflected back into space and causing temperatures to drop. It is a positive feedback; as sea ice/snow cover increases, surface temperatures continue to decrease. This impacts the atmospheric layers above leading to greatly decreased temperature.

(3) Modified the relevant sentence: "The intense surface cooling is primarily responsible for activating the ice-albedo effect; a positive feedback which enhances surface cooling as sea ice and snow cover increases, causing a greater amount of radiation to be reflected back into space. The result is similar to the establishment of a nuclear winter, albeit via a slightly different mechanism."

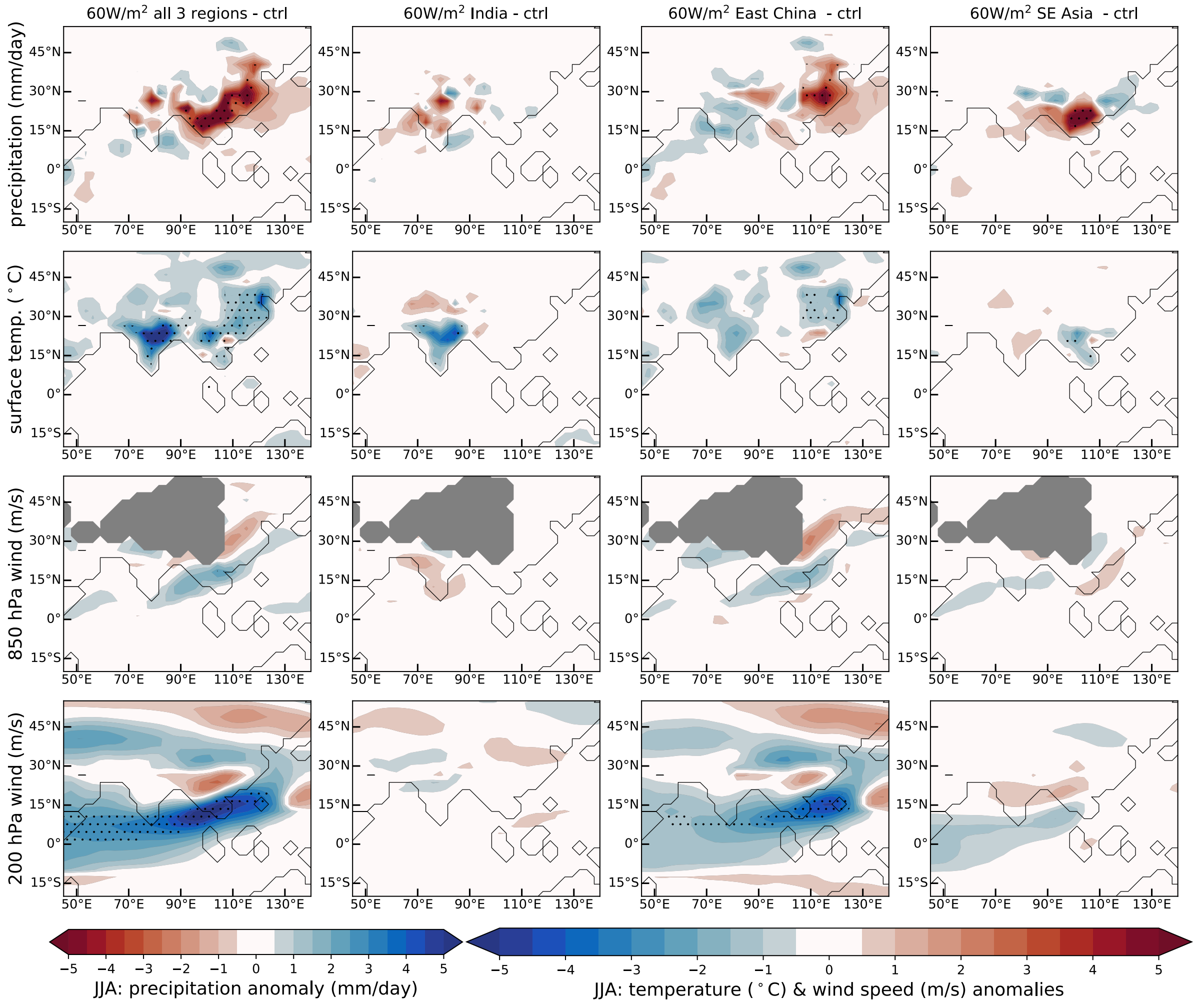
(1) I could not understand how the aerosol forcing applied to eastern China increases precipitation over India. Are the changes statistically significant? There is still a decrease in surface temperature over India (Figure 11) without aerosol forcings. What could be the potential reason for an increase in precipitation? Please provide a physical explanation.

(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 process is highly nontrivial and we are collaborating with the Herbert et al. team exactly to discover the mechanisms in action. Our initial theory is that although the absorbing aerosol forcing causes the low-level southwesterly wind in the band 0-20°N to weaken, there is a thin band around 20-25°N at high levels of forcing where the wind speed increases. We tend to attribute the increase in precipitation over North India to the increased wind speed, which brings an influx of moisture from the Arabian Sea.

Additionally, figures have been modified so that stippling indicates statistically significant changes, defined as where the change is greater than double the interannual June-July-August variability (standard deviation). Thus, although there is a slight increase in precipitation over North India, it is not statistically significant by our condition.

(3) Added stippling to figures (see revised Figure 11 below) and modified a sentence in Section 5: "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

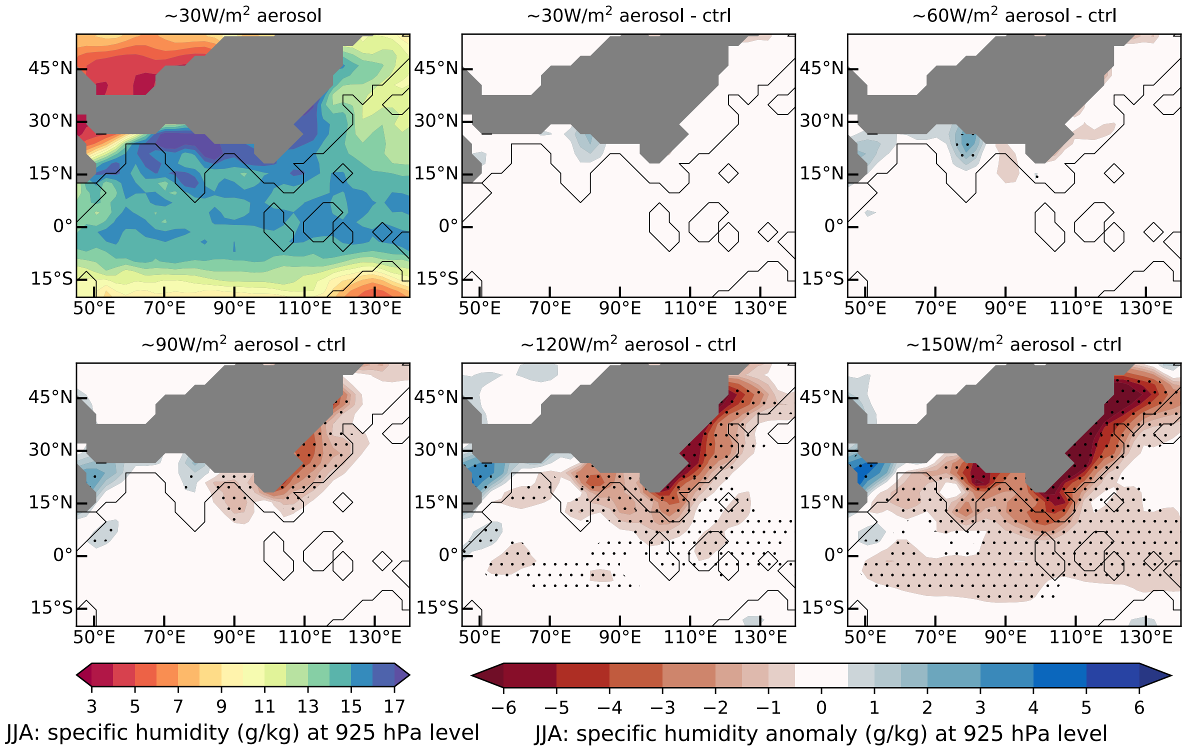
between East China and India in relation to local absorbing aerosol forcing has been shown in Herbert et al. (2022); however, further study is required to fully understand the underlying mechanisms.”

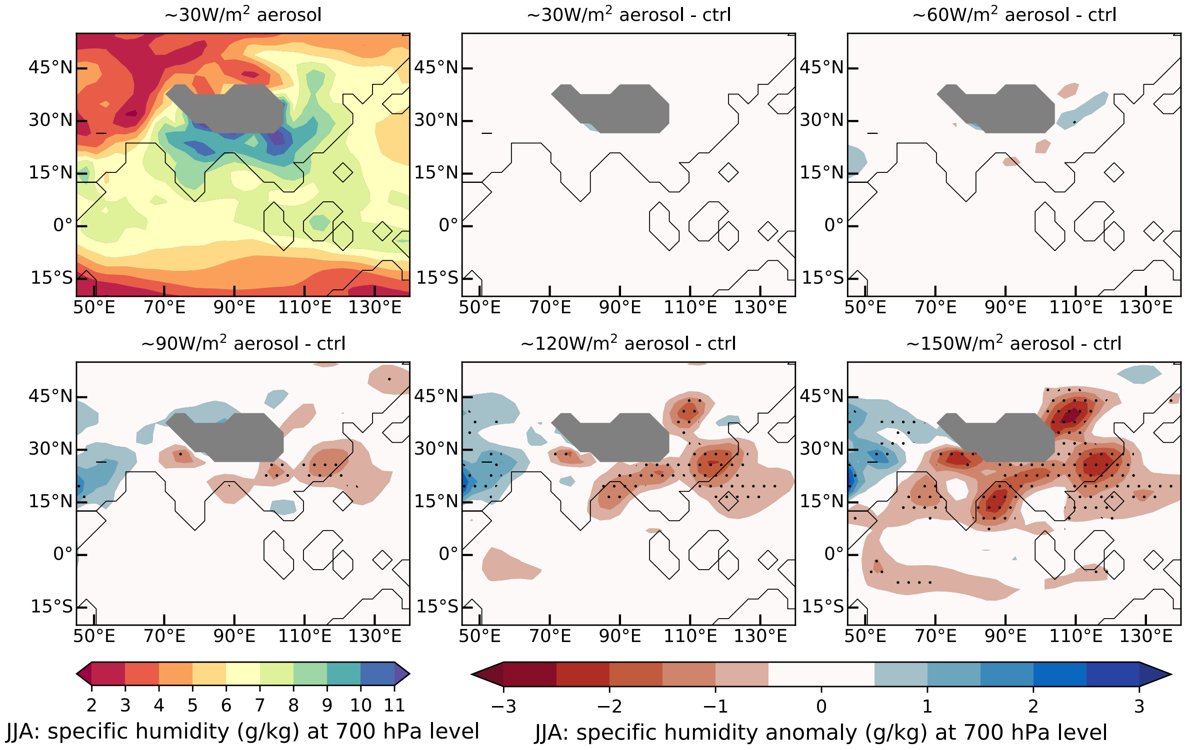


(1) The concept of the advection of dry air from Siberia is not well interpreted. It would be better to have a look at the responses of specific humidity to aerosol forcings.

(2) We agree with the reviewer that specific humidity is a key variable to consider. From Figure 6, we see a reduction in precipitable water over Southeast Asia and from Figure 7, an increase in 850 hPa wind speed from Southeast Asia to eastern Siberia. Thus, there is advection of dry air from Southeast Asia to eastern Siberia, leading to a reduction of precipitation in eastern Siberia. In support of this theory, there is a decrease in specific humidity at low levels over Southeast Asia and East China. In particular, we see the specific humidity at 925 hPa decrease around 45°N, 125°E, which is outside the area of applied aerosol forcing.

(3) Added an extra figure to show specific humidity at 700 & 925 hPa (example below).


~30W/m^2 aerosol
~30W/m^2 aerosol - ctrl
~60W/m^2 aerosol - ctrl
~90W/m^2 aerosol - ctrl
~120W/m^2 aerosol - ctrl
~150W/m^2 aerosol - ctrl
45°N
30°N
15°N
0°
15°S
50°E
70°E
90°E
110°E
130°E
3 5 7 9 11 13 15 17
JJA: specific humidity (g/kg) at 925 hPa level
−6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
JJA: specific humidity anomaly (g/kg) at 925 hPa level


~30W/m^2 aerosol
~30W/m^2 aerosol - ctrl
~60W/m^2 aerosol - ctrl
~90W/m^2 aerosol - ctrl
~120W/m^2 aerosol - ctrl
~150W/m^2 aerosol - ctrl
45°N
30°N
15°N
0°
15°S
50°E
70°E
90°E
110°E
130°E
2 3 4 5 6 7 8 9 10 11
JJA: specific humidity (g/kg) at 700 hPa level
−3 −2 −1 0 1 2 3
JJA: specific humidity anomaly (g/kg) at 700 hPa level

Technical comments:

(1) Maps of good quality are not well superimposed on the spatial figures. They seem at a very coarse resolution and distorted.

(2) We use a reasonably coarse horizontal resolution of approximately 2.8 degrees (T42 spectral resolution). This is the highest resolution available with the PLASIM model. The figures reflect the model resolution. The coastlines are drawn using the model's land-sea map, so as to accurately reflect the horizontal resolution of the model and not be misleading. For future work, it is hoped that similar experiments with a gradually varying forcing might be performed with the WRF model (or similar).

(3) No changes implemented.