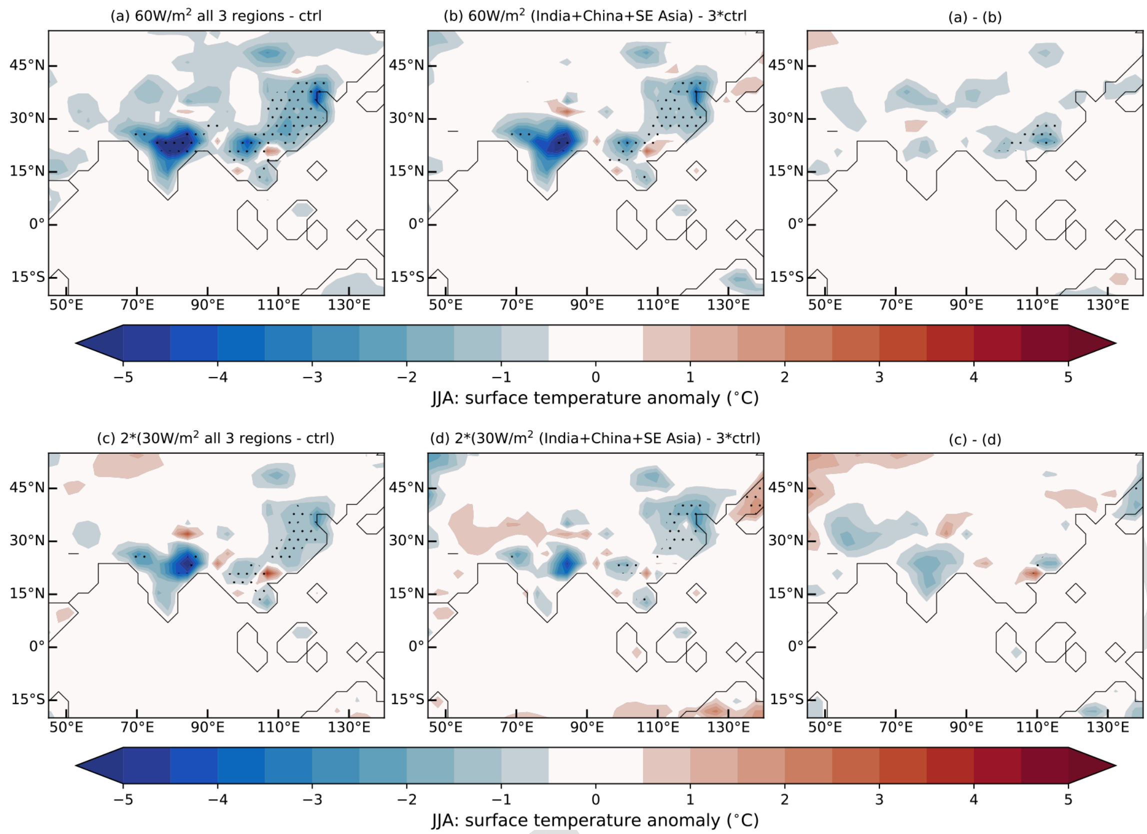

Figure 14. Surface temperature, taken as 100-year June–July–August average, for 60 W m^{-2} **(a, b)** and 30 W m^{-2} **(c, d)** absorbing aerosol forcing, where the latter has been scaled by a factor of 2. Panels **(a, c)** are the anomaly against control of simultaneously forcing all three regions. Panels **(b, d)** are the anomaly against control of the linear combination of separately forced regions (India, East China and Southeast Asia). Panels **(a)**–**(b)** and **(c)**–**(d)** are the differences between simultaneously forced regions **(a, c)** and a linear combination of individually forced regions **(b, d)**. Stippling is where the anomaly exceeds double the JJA interannual variability of the control simulation.

Table 3. Values of area-averaged surface temperature (°C) at 30 and 60 W m^{-2} absorbing aerosol forcing for different regions (rows) and model simulations (columns). Values are taken as 100-year June–July–August averages. TS8

	Aerosol + all (temperature °C)		(1) Aerosol + India (temperature °C)		(2) Aerosol + eastern China (temperature °C)		(3) Aerosol + Southeast Asia (temperature °C)		~~Average~~ of (1), (2) and (3) (temperature °C)	
Forcing ~~range~~ (W m^{-2})	30	60	30	60	30	60	30	60	30	60
Northern India	~~29.3~~	~~27.3~~	~~29.6~~	~~28.4~~	~~30.2~~	~~29.3~~	~~31.0~~	~~30.8~~	~~30.3~~	~~29.5~~
Southern India	~~24.5~~	~~23.4~~	~~24.6~~	~~23.8~~	~~25.0~~	~~24.7~~	~~25.5~~	~~25.5~~	~~25.0~~	~~24.7~~
Eastern China	~~23.0~~	~~21.9~~	~~23.6~~	~~23.6~~	~~23.1~~	~~22.4~~	~~23.5~~	~~23.5~~	~~23.4~~	~~23.2~~
Southeast Asia	~~23.8~~	~~22.8~~	~~24.0~~	~~24.1~~	~~24.0~~	~~24.1~~	~~23.6~~	~~23.2~~	~~23.9~~	~~23.8~~

column of Fig. 13). Similarly, there is little difference in the response between 60 W m^{-2} and 2 × 30 W m^{-2}. In Sect. 4, we noted that the response of variables between 30, 60, and 90 W m^{-2} was comparable. Generally, there is a fair degree of linearity in the response in terms of forcing intensity and combinations of forcing regions.

These results are in contrast to Herbert et al. (2022), who found a non-linear response when northern India and eastern China were forced separately, compared to being forced simultaneously. Their experiments were also conducted using an intermediate-complexity climate model, with an approximate treatment of scattering and absorbing aerosols, but considered the effects of removing them rather than adding them. The differences are likely related to the areas of applied forcing; Herbert et al. (2022) apply aerosol forcing to a limited region along the north boundary of India, while we apply aerosol forcing across the entirety of India. The limited region of application by Herbert et al. (2022) may elicit stronger orographic and advective effects, leading to a greater degree of non-linearity in the response. On the other

Table 4. Values of area-averaged precipitation (mm d^{-1}) at 30 and 60 W m^{-2} absorbing aerosol forcing for different regions (rows) and model simulations (columns). Values are taken as 100-year June–July–August averages.

	Aerosol + all (precip. mm d^{-1})		(1) Aerosol + India (precip. mm d^{-1})		(2) Aerosol + eastern China (precip. mm d^{-1})		(3) Aerosol + Southeast Asia (precip. mm d^{-1})		~~Average~~ of (1), (2) and (3) (precip. mm d^{-1})	
Forcing ~~range~~ (W m^{-2})	30	60	30	60	30	60	30	60	30	60
Northern India	~~6.1~~	~~5.3~~	~~6.0~~	~~5.4~~	~~6.7~~	~~7.1~~	~~6.2~~	~~6.1~~	~~6.3~~	~~6.2~~
Southern India	~~7.0~~	~~7.5~~	~~6.8~~	~~6.5~~	~~7.5~~	~~8.6~~	~~6.8~~	~~6.8~~	~~7.0~~	~~7.3~~
Eastern China	~~7.4~~	~~5.2~~	~~8.2~~	~~8.3~~	~~7.2~~	~~5.4~~	~~8.4~~	~~8.9~~	~~7.9~~	~~7.5~~
Southeast Asia	~~7.9~~	~~5.7~~	~~9.6~~	~~9.5~~	~~9.3~~	~~9.0~~	~~8.4~~	~~6.5~~	~~9.1~~	~~8.3~~

hand, Shindell et al. (2012) noted generally linear responses of summer precipitation to forcing combinations involving aerosols and greenhouse gases across zonally averaged latitudinal bands. Similarly, on a global scale, Gillett et al. (2004) find no evidence of non-linearity in the combination of responses to greenhouse gases and sulfate aerosols with the HadCM2 model. Guo et al. (2016) find that the reduction in precipitation across Southeast Asia due to higher global sulfur dioxide emissions is comparable to the linear combination of precipitation from simulations that consider local and remote sources of sulfur dioxide independently. However, a similar linearity is not observed in the response to increases in black carbon aerosols. Further work is required to quantify the linearity in response to aerosol forcing across different models and how model biases can impact the results.

6 Conclusions

The strength of the South Asian and East Asian monsoons is largely determined by processes affecting the sea surface temperature, greenhouse gases, and aerosols. Here, we have conducted a parametric study with an intermediate-complexity climate model to assess the roles of absorbing aerosol and greenhouse gas forcing on the South Asian and East Asian monsoons. In addition, we have identified the level of regional forcing at which the monsoon system breaks down in terms of a significant reduction in precipitation.

Absorbing aerosol forcing, which we apply through a combination of mid-tropospheric heating and surface cooling in our model, causes decreasing surface temperatures, mid-level warming, weakening circulation, and a reduction in (convective) precipitation. As the forcing increases, the precipitation declines much faster than the precipitable water, indicating that it is due to a lack of precipitation efficiency related to changes in the stratification of the atmosphere, rather than due to a lack of moisture. Advection of dry air from eastern China leads to a reduction in precipitation in eastern Siberia, which is outside of the area being forced. On removal of the absorbing aerosol forcing, we find that the monsoon system recovers fully, indicating that there is no hysteresis in our model simulations. Doubling carbon dioxide concentration partially mitigates the effects of the absorbing aerosol forcing, through warmer surface temperatures enabling greater moisture take-up, but further weakens the large-scale circulation. We find that, when considering realistic ranges of applied forcings, 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 Asian and East Asian monsoons.

The strongest regional responses, particularly in regards to the circulation, are attributed to absorbing aerosol loading over eastern China. Although the precipitation decline for each region directly corresponds to applying forcing to that region, there is a remote connection between eastern China and India. Forcing applied to eastern China leads to a slight increase in precipitation over India, which is in contrast with the response when forcing is applied to India. When both regions are forced simultaneously, there is a reduction in precipitation over India, but the reduction is much less than for Southeast Asia or eastern China. Comparing simulations where the regions have been forced separately to the simulation where the regions have been forced simultaneously, the results are qualitatively similar, indicating a fair degree of linearity in the response.

We have characterised regional regimes in terms of area-averaged precipitation, precipitable water, and surface temperature. India is separated into northern and southern regions due to the significant variance in their responses. Southern India is the least affected region, likely due to its peninsular nature. The precipitation response of northern India and Southeast Asia to increasing absorbing aerosol forcing is an approximately linear decline, with Southeast Asia showing a stronger negative sensitivity than northern India. For eastern China, there is an sharp transition at around 60 W m^{-2} to a regime where the precipitation is close to zero, indicating tipping behaviour. In terms of the precipitable water, it remains relatively constant for all regions until 60 W m^{-2}; thereafter the precipitable water linearly declines with further increases in forcing. The surface temperature behaves similarly to the precipitable water but becomes much more sensitive to the forcing beyond 60 W m^{-2} and declines non-linearly.

We note the importance of aerosol loading over eastern China and the competition between aerosol loading over India in determining the response of the Indian region to fu-