Nonlinear Response of Asian Summer Monsoon Precipitation to Emission Reductions in India and China

Ross Herbert[1,1], Laura J Wilcox[2,2], Manoj Joshi[3,3], Ellie Highwood[4,4], and Dave Frame[5,5]

[1]University of Oxford
[2]National Centre for Atmospheric Science
[3]University of East Anglia
[4]University of Reading
[5]New Zealand Climate Change Research Institute

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Abstract

Now published: https://doi.org/10.1088/1748-9326/ac3b19 Anthropogenic aerosols over South and East Asia currently have a stronger impact on the Asian Summer Monsoon (ASM) than greenhouse gas emissions, yet projected aerosol emission changes in these regions are subject to considerable uncertainty in timescale, location, emission type, and even the sign of the change, implying large uncertainties in future ASM change. In addition, aerosol changes in either South or East Asia cause circulation anomalies that affect both countries and neighbouring regions. We use a circulation/climate model to demonstrate that the sum of ASM responses to individual aerosol emission reductions in each region is very different to the response to simultaneous reductions in both regions, implying the ASM response to aerosol emissions reductions is highly nonlinear. The phenomenon is independent of whether aerosols are scattering or absorbing, and is driven by large-scale teleconnections between the two regions. The nonlinearity represents a new source of uncertainty in projections of ASM changes over the next 30-40 years, and limits the utility of country-dependent aerosol trajectories when considering their Asia-wide effects. To understand likely changes in the ASM due to aerosol reductions, countries will need to accurately take account of emissions reductions from across the wider region, rather than approximating them using simple scenarios and emulators. The nonlinearity in the response to forcing therefore presents a regional public goods issue for countries affected by the ASM, as the costs and benefits of aerosol emissions reductions are not internalised; in fact, forcings from different countries work jointly to determine outcomes across the region.

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Ross Herbert[1,†], Laura J. Wilcox[2], Manoj Joshi[3], Ellie Highwood[1], Dave Frame[4]

[1] Department of Meteorology, University of Reading, Reading, RG6 6BB, United Kingdom
[2] National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, RG6 6BB, United Kingdom
[3] Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
[4] New Zealand Climate Change Research Institute, University of Wellington, PO Box 600, New Zealand
[†] Now at Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom

E-mail: ross.herbert@physics.ox.ac.uk

Abstract

Anthropogenic aerosols over South and East Asia currently have a stronger impact on the Asian Summer Monsoon (ASM) than greenhouse gas emissions, yet projected aerosol emission changes in these regions are subject to considerable uncertainty in timescale, location, emission type, and even the sign of the change, implying large uncertainties in future ASM change. In addition, aerosol changes in either South or East Asia cause circulation anomalies that affect both countries and neighbouring regions. We use a circulation/climate model to demonstrate that the sum of ASM responses to individual aerosol emission reductions in each region is very different to the response to simultaneous reductions in both regions, implying the ASM response to aerosol emissions reductions is highly nonlinear. The phenomenon is independent of whether aerosols are scattering or absorbing, and is driven by large-scale teleconnections between the two regions. The nonlinearity represents a new source of uncertainty in projections of ASM changes over the next 30-40 years, and limits the utility of country-dependent aerosol trajectories when considering their Asia-wide effects. To understand likely changes in the ASM due to aerosol reductions, countries will need to accurately take account of emissions reductions from across the wider region, rather than approximating them using simple scenarios and emulators. The nonlinearity in the response to forcing therefore presents a regional public goods issue for countries affected by the ASM, as the costs and benefits of aerosol emissions reductions are not internalised; in fact, forcings from different countries work jointly to determine outcomes across the region.

Keywords: Asian summer monsoon, aerosol-radiation interactions, climate change, climate impacts, public goods issue

1. Introduction

Almost half of the world's population rely on the Asian summer monsoon (ASM) precipitation for agriculture, energy, industry, and local water resources. Small changes in the onset, intensity, and duration of the ASM can result in considerable socio-economic impacts. The ASM is driven by the large-scale meridional temperature gradient that occurs during boreal spring as a result of intense solar heating of the land surface in contrast to the slower ocean heating. Increasing global temperatures due to greenhouse gases (GHGs) enhance the land-sea temperature and pressure gradients, and strengthen the ASM (Lau and Kim 2017, Sutton *et al* 2007) whereas anthropogenic aerosol emissions weaken monsoon circulation and the ASM via large-scale preferential cooling of the northern hemisphere and localised surface cooling of the land (Lau and Kim 2017, Polson *et al* 2014, Song *et al* 2014, Undorf *et al* 2018, Wilcox *et al* 2020). An observed drying trend in ASM precipitation in the latter half of the 20th century opposed the impacts of GHG emissions, and studies have largely attributed this trend to anthropogenic aerosol emissions (Bollasina *et al* 2011, Dong *et al* 2019, Lau and Kim 2017, Li *et al* 2015, Liu *et al* 2019, Song *et al* 2014). Driven by concerns about air quality and human health, there are likely to be large reductions to aerosol emissions over the next two to three decades and these will have important impacts on the ASM. The diversity in emission pathways under different Shared Socioeconomic Pathways (SSPs) therefore presents a key uncertainty in climate projections over the near-term future (Bartlett *et al* 2018, Samset *et al* 2019, Wilcox *et al* 2020).

Aerosols modify the heating profile of the atmosphere and perturb surface fluxes via aerosol-radiation interactions (ARI). Sulphate aerosol (SU) scatters almost all of the radiation it interacts with and acts to cool the surface, whereas carbonaceous aerosol (BC) absorbs some of the radiation and thus acts to simultaneously cool the surface and produce localized heating of the aerosol layer. Aerosols can also perturb cloud properties via aerosol-cloud interactions (ACI); an increase in aerosol availability may enhance cloud brightness, reducing surface fluxes, and suppress the warm rain process. The widespread emission of SU precursors in South and East Asia weakens the meridional temperature gradient and associated ASM circulation and precipitation (Westervelt *et al* 2020, Kim *et al* 2016a, Dong *et al* 2016), whilst BC emissions may promote anomalous convection and a redistribution of heat and moisture, changing the distribution of precipitation and the onset of the ASM (Collier and Zhang 2009, Lau *et al* 2006, Meehl *et al* 2008, Menon *et al* 2002). Although the instantaneous responses to SU and BC are different the net response from aerosol is an overall weakening of the ASM driven by the surface cooling that both species exert (Persad *et al* 2017).

Most future changes in Asian anthropogenic aerosol emissions will occur in India and China, though future pathways are diverse due to uncertainty in the timescale, sign, and location of emission changes, and the future composition (SU vs BC) of the aerosol (Lund *et al* 2019, Riahi *et al* 2017, Samset *et al* 2019). Indeed, recent observations show that emissions in China have been decreasing since 2010, whilst emissions in India continue to rise, suggesting very different future rates of aerosol reductions (Li *et al* 2017, Zheng *et al* 2018). In this study we focus on how projected future aerosol reductions in China and/or India will impact the ASM. We achieve this by exploring the climate response to regional emission reductions, and the potential for nonlinear interactions between them, in dedicated modelling experiments.

2. Materials and Methods

We use the Intermediate Global Circulation Model version 4 (IGCM4; Joshi *et al* 2015), which has been previously used for studies related to climate, aerosol, and tropical meteorology (Joshi *et al* 2003, Cnossen *et al* 2011, Shine *et al* 2003, van der Wiel *et al* 2016, Ratna *et al* 2020, 2021, Ferraro *et al* 2015) and reproduces the observed timing and magnitude of the ASM (figure 1). Here we employ a monthly-varying sea-surface temperature climatology and observationally constrained idealized aerosol perturbations over India and China. The idealized nature of the setup helps to clarify the mechanisms underlying the response whilst maintaining the performance and capabilities of CMIP models.

2.1 Model configuration and representation of aerosol

The IGCM4 is a global spectral primitive equation climate model that includes schemes for radiation, interactive land-surface properties, dry and moist convection, precipitation, and clouds. The model configuration has 35 layers in the vertical up to 0.1 hPa and a horizontal resolution of ~2.8 degrees (T42). A monthly-varying climatology of SST is taken from the NOAA Optimum Interpolation V2 product for 1982-2009 (Reynolds *et al* 2002). An evaluation by Joshi *et al* (2015) shows that this configuration reproduces observed precipitation patterns with a bias within 1 standard deviation of the equivalent CMIP5 ensemble and therefore within the range of state-of-the-art GCMs. The top-of-atmosphere net energy imbalance is also similar to other climate models (1 – 2 W m^{-2}), as is the equilibrium climate sensitivity of 2.1 K.

In these simulations the non-interactive aerosol is incorporated into the radiation scheme, which results in a perturbation to the heating profile and fluxes of longwave and shortwave radiation. Simulated aerosol perturbations are designed to capture the observed magnitude, annual cycle, and geographical location of anthropogenic aerosol perturbations in Asia, and the IGCM4 reproduces observed precipitation well when using climatological ARI (figure 1). By considering only ARI we avoid the uncertainties associated with aerosol emissions and microphysics (e.g., Rothenberg *et al* 2018, Simpson *et al* 2014), which are reflected in large differences in the magnitude and pattern of anthropogenic aerosol radiative forcing in CMIP6 (Wilcox *et al* 2020), and instead we focus on the potential for nonlinearities in the response to regional forcing.

The annual mean satellite-retrieved aerosol optical depth (AOD) climatology from MODIS (product MOD08_M3 v6.1 combined Dark Target and Dark Blue) shown in figure 2a was used to collocate the geographical location of the primary emission sources in India and China. For India these heavy industrial regions are located to the NW over Pakistan and along the foothills of the Himalayas on the Indo-Gangetic Plain. In China the primary source regions include the North China Plain and Yangtze River Delta to the east and Sichuan Basin to the west. Figure 2b demonstrates that we capture these dominant source regions. Idealized vertical profiles for the anthropogenic aerosol are based on observations from each region: in India the simulated aerosol extends from the surface up to 600 hPa or 3.5 km (Sarangi *et al* 2016, Brooks *et al* 2019, Gautam *et al* 2010, Nair *et al* 2016); and in China the aerosol extends from the surface to 800 hPa or 2 km (Tian *et al* 2017, de Leeuw *et al* 2018). The AOD climatology in figure 2a masks the pronounced seasonal variations in AOD that are observed in Asia. To account for this, we include an annual cycle for both regional aerosol perturbations, shown in figure 2c. In India the AOD increases throughout the spring then rapidly decreases as the monsoon precipitation enhances scavenging processes. In China the industrial regions are less impacted by monsoon precipitation, and sustain enhanced AOD throughout the monsoon season.

2.2 Experiments

Using present-day aerosol concentrations and spatial distributions over both India and China as our 'control' states, we perform experiments for a total reduction over India only (R_{India}), China only (R_{China}), and over both regions simultaneously (R_{Asia}). By summing the individual reductions (R_{India} + R_{China}) and comparing to R_{Asia} we are able to quantify nonlinear behaviour in the response to emission pathways. Seasonal means for the pre-monsoon (April-May) and monsoon (June-July-August) season are presented using the final 40 years of the integration, following a 10-year spin up period. We perform separate 50-year experiments to examine the effects of SU and BC, since there is uncertainty in aerosol properties and how they will change in time.

3. Results

3.1 Pre-monsoon season

Simulated present-day rainfall during the pre-monsoon (figures 3a, 3b) is concentrated over the Tibetan Plateau (TP) and in a belt from West to East China.

The removal of anthropogenic aerosol throughout Asia (R_{Asia}) primarily increases rainfall over the Tibetan Plateau (TP) (figures 3c, 3d); BC reductions produce a stronger response (up to +40%) than SU (up to +20%) and additionally cause widespread and robust drying over NE Asia and the NW Pacific Ocean by -20%. There is little response to either aerosol species south of 25° N, which covers most of India and S China. The redistribution of precipitation is explained by the suppression (removal of BC) or promotion (removal of SU) of localized ascent and the subsequent redirection of air flow downstream (see figure S1). For both aerosol species there is enhanced flow across the TP, enhancing the transport of moisture and precipitation to the region, whilst for BC there is reduced transport to the NE of China.

Reducing aerosol emission in China alone (R_{China}) prevents the increase in pre-monsoon precipitation over the Tibetan Plateau (figures 3e, 3f) that is observed in the R_{Asia} experiment, but now we see a reduction in precipitation over the Bay of Bengal by up to -40%. The reduction of BC and SU over China alone exerts a relatively stronger local effect on the atmospheric circulation than when reduced alongside Indian emissions (see figure S1) which points towards a connection between the perturbation of the flow over the Tibetan Plateau and the localized response in China. The drying observed over the Bay of Bengal is likely an upstream effect of robust anomalous descent in China.

The removal of aerosol produces strong nonlinearity in the pre-monsoon response below 25° N regardless of the species. In the R_{Asia} experiments there is no significant change to precipitation over much of India and China (figures 3c, 3d), yet the summed response from R_{India}+R_{China} (figures 3i, 3j) show pronounced drying over the Bay of Bengal and enhanced precipitation over S India. The strong dipole in the localised response from SU removal over E China (figure 3j) is also absent in the R_{Asia} experiment (figure 3d).

3.2 Monsoon season

During the monsoon season (figure 4) aerosol reductions in R_{Asia} generally result in enhanced precipitation (up to +20% for BC; +40% for SU) across much of China with drying up to -20% to the south, most notably over S India and the SW Pacific Ocean. The reduction of SU produces anomalous low pressure and warming of the boundary layer, producing a pronounced northward shift and strengthening of the low-level jet, which drives the observed dipole in precipitation response; there is also an enhanced northerly component of the jet over E China. The reduction of BC similarly warms the surface but to a lesser extent than SU, producing a similar pattern of precipitation response as the flow over the Himalayas is enhanced. The general strengthening of the ASM in response to aerosol reductions is consistent with other studies (Wilcox *et al* 2020, Samset *et al* 2016, Sherman *et al* 2021) but as shown here, the magnitude of the response is sensitive to the relative contribution of reductions from SU and BC species.

In the monsoon season the reduction of BC aerosol in China alone (figure 4e) causes significant drying of up to +40% over much of India and the Bay of Bengal, as well as over much of China. The removal of BC acts to divert the low-level jet and accompanying precipitation southwards over the W Pacific and weakens the ASM circulation. A similar response was seen in the R_{Asia} experiment, but as in the pre-monsoon season, the dynamical response to the BC reduction is stronger when reduced in China alone. The reduction in SU from China alone (figure 4f) shows a similar spatial pattern to R_{Asia} but the dipole in precipitation response is weaker (over China R_{Asia} = +40%; R_{China} = +20%). The warming that is induced by the removal of SU over China is sufficient to impact the jet position but the effect is considerably enhanced when both India and China reduce their emissions simultaneously; this result is consistent with a recent analysis of earth-system models (Sherman *et al* 2021).

Similar to the pre-monsoon season there exists considerable nonlinearity in the monsoon precipitation response from emissions reductions in India and China. The starkest contrast between R_{Asia} (figures 4c, 4d) and R_{India}+R_{China} (figures 4i, 4j) is in the magnitude of the precipitation response, which is suppressed by nonlinear behaviour across much of Asia, especially for BC aerosol. For SU the pattern of the response is consistent across China, but India experiences a reversal of the N-S dipole. In contrast, BC nonlinearity manifests via robust changes to the spatial pattern of the response: BC removal from China produces significant drying over India (figure 4e) yet when emissions are removed in both regions simultaneously this is entirely suppressed (figure 4c); a similar response occurs over the SW Pacific and South China Sea. India and S China tend to exhibit particular sensitivity to nonlinearity; these regions are co-located with the center of the low-level jet and are therefore particularly prone to latitudinal shifts in the jet center (see figure S1).

4. Discussion

Figure 5 summarises the degree of nonlinearity in the ASM (see table S1 for values), which is evident as the difference between top panels (a, b, e, f), and bottom panels (c, d, g, h), respectively. The nonlinearity does not manifest as a persistent bias between the regions - rather the magnitudes of the precipitation responses are suppressed when aerosol is reduced in both regions together, especially during the monsoon season. The nonlinearity is generally stronger for BC aerosol, likely due to its direct impact on localized circulation (Westervelt *et al* 2020), which implies that the ability to predict aerosol composition in the future (proportions of BC and SU) will not remove the nonlinearity.

Current trends show a decreasing SU burden over China. Our simulations suggest this will increase monsoon precipitation, though if SU emissions were concurrently reduced over India the precipitation is further enhanced over China, at the expense of a drying over S India. Concurrent reductions in SU throughout the northern hemisphere will shift the monsoon low-level jet further south (Song *et al* 2014, Chen *et al* 2018), which may counteract the drying we observe in S India. BC removal over China in isolation will produce widespread cooling which weakens the monsoon circulation, especially over India, whereas BC removal in both India and China suppresses the response and results in enhanced precipitation across much of Asia.

The nonlinearity seen in our results can be thought of as essentially a new source of uncertainty in regional projections of Asian monsoon impacts over the next 30 years. Even in a linear system, the effects of regional, or country-dependent, reductions in aerosol emissions would need to be considered together when examining effects on regional precipitation across Asia; reducing such uncertainties, especially in BC emissions, has already been noted for projections using CMIP models (Sherman *et al* 2021). However, the strong nonlinearity found above means that even approximations to trajectories of country-dependent aerosol reductions are of very limited use when considering their Asia-wide effects. In other words, studies that attempt to emulate monsoon response to aerosol reductions using a small number of scenarios are not suitable for properly assessing the change in precipitation, and related impacts, associated with reductions in aerosol emissions in South and East Asia. A rethink is therefore needed in terms of how the uncertainties in future aerosol trajectories in Asia are incorporated into climate model projections.

Although future changes to aerosol emissions are projected to predominantly occur over Asia (Wilcox *et al* 2020), the impact from changes in non-local sources of aerosols may contribute to additional nonlinearity. Although a number of studies show the potential for remote emissions to influence Asian climate, there is a range of estimates of the relative importance of this contribution (Song *et al* 2014, Dong *et al* 2016, Wang *et al* 2017, Guo *et al* 2016, Undorf *et al* 2018). Historically, important sources of remote emissions driving Asian responses have been Europe and North America. In future, as the distribution and composition of aerosol and precursor emissions changes, other regions may become more important, giving rise to as yet unexplored remote drivers of Asian precipitation change.

Further uncertainties in the near-future monsoon response to aerosol may arise from interactions with the response to greenhouse gases, either through the interaction of the dynamical responses themselves, or through a modification of the aerosol radiative forcing by, for example, a warming-induced cloud response change that influences aerosol-cloud interactions. On shorter timescales, aerosol can amplify the monsoon response to ENSO (Kim *et al* 2016b), adding further complexity to regional projections. Future work should examine how the nonlinearity is affected by other drivers including the roles of increasing GHG concentrations and fully interactive aerosol. Introducing these drivers necessitates the use of ensembles of fully coupled ocean-atmosphere models that simulate both climate change and internal variability, representing a large computational commitment if multiple scenarios are to be explored.

The direct health benefits of aerosol emissions reductions programmes are largely confined to the countries in which the programmes are undertaken. The same is not true of the climate impacts of those programmes, which are experienced outside the originating country as well as inside it. As we have demonstrated, the impacts of emission reduction programmes combine nonlinearly, and across borders. Therefore, from the perspective of a government's climate/aerosol mitigation effort, understanding regional aerosol-climate interactions does not provide adequate information about the regional climate response; to anticipate the effects of their programmes, they also need a better understanding of each country's future aerosol emission trajectories. In the context of southern and eastern Asia, the effects of aerosol reduction programmes are entwined via multinational actions, i.e., the process of aerosol reduction presents a regional, rather than national, public goods issue (Kaul 2003) for countries affected by the ASM. There is thus a potential role for joint action by such countries, so that the impacts of emissions programmes can be ameliorated for the benefit of all.

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Figures

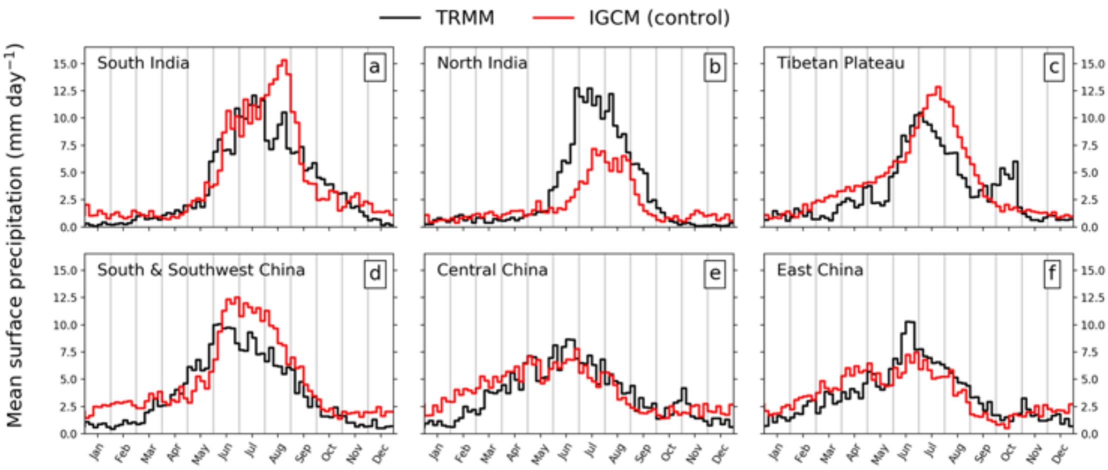

Figure 1. Comparison of simulated mean annual surface precipitation rates with satellite observations from the Tropical Rainfall Measuring Mission Project (TRMM) over six regions in Asia. Simulated data (red line) is shown for the present-day experiment with sulphate aerosol. Daily TRMM data from 2000 to 2017 (black line) is taken from the TRMM daily Near Real-Time Precipitation product (L3, 0.25 degree, V7). Both datasets are used to obtain a 5-day rolling mean annual cycle of precipitation rate (mm day^{-1}) over the six regions shown in figure 2d.

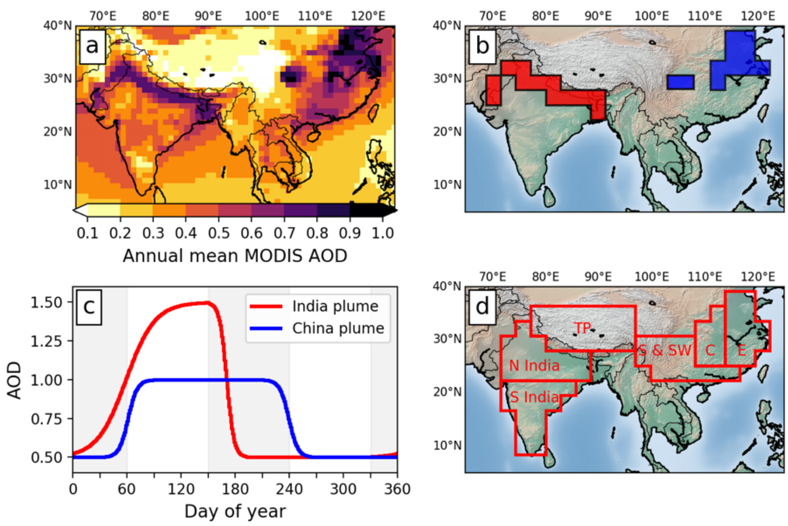

Figure 2. Experimental setup showing: (a) MODIS annual mean AOD climatology (2001-2020); (b) spatial distribution of the simulated aerosol plumes; (c) annual cycle of the AOD for the two regions; and (d) geographical locations of each region used for the analysis of regional precipitation responses shown in figure 5.

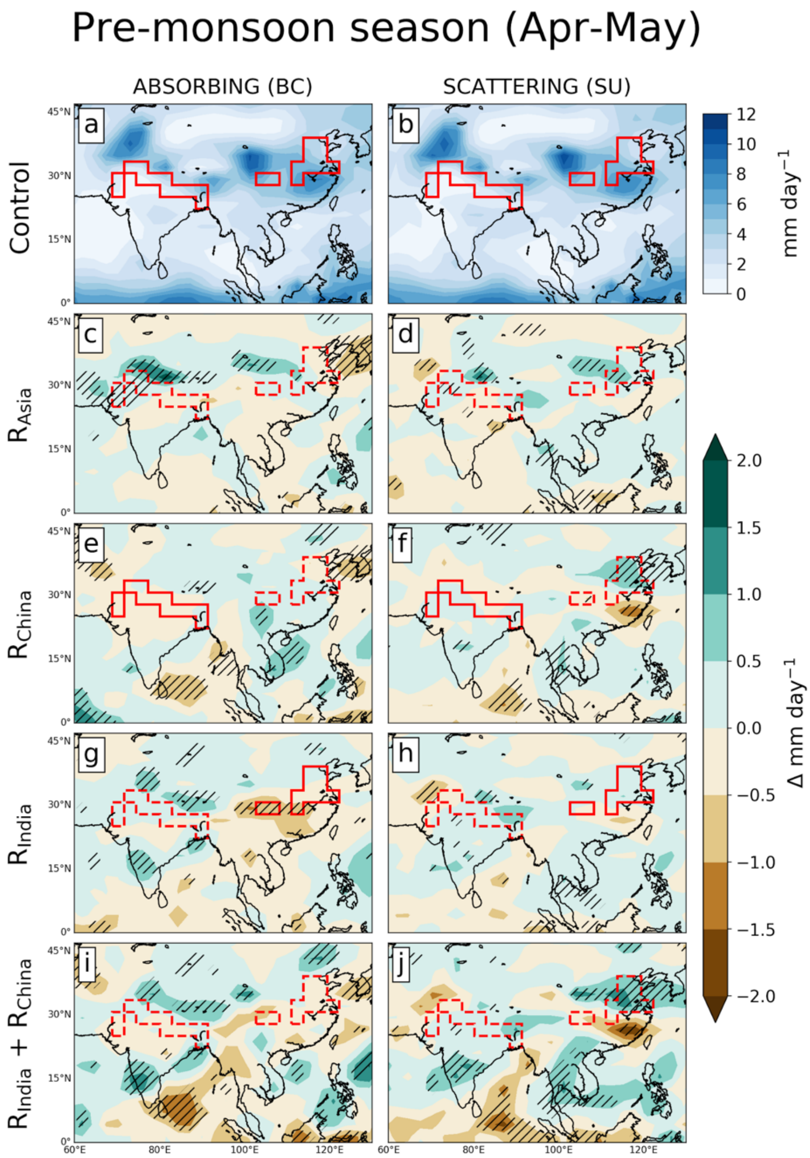

Figure 3. Pre-monsoon (April and May) seasonal mean precipitation rate in present day simulations (a – b), and the absolute response due to aerosol reductions in experiments R_{Asia} (c – d), R_{China} (e – f), R_{India} (g – h), and the summed contribution R_{China}+R_{India} (i – j). The column on the left is for absorbing (BC) aerosol and the column on the right is for scattering (SU) aerosol. Hatched areas show a statistically significant change at or above a confidence of 90%. Solid red boxes show the location of the regional perturbation, and dashed boxes where the perturbation has been removed. A version showing percentage change in precipitation is shown in figure S2.

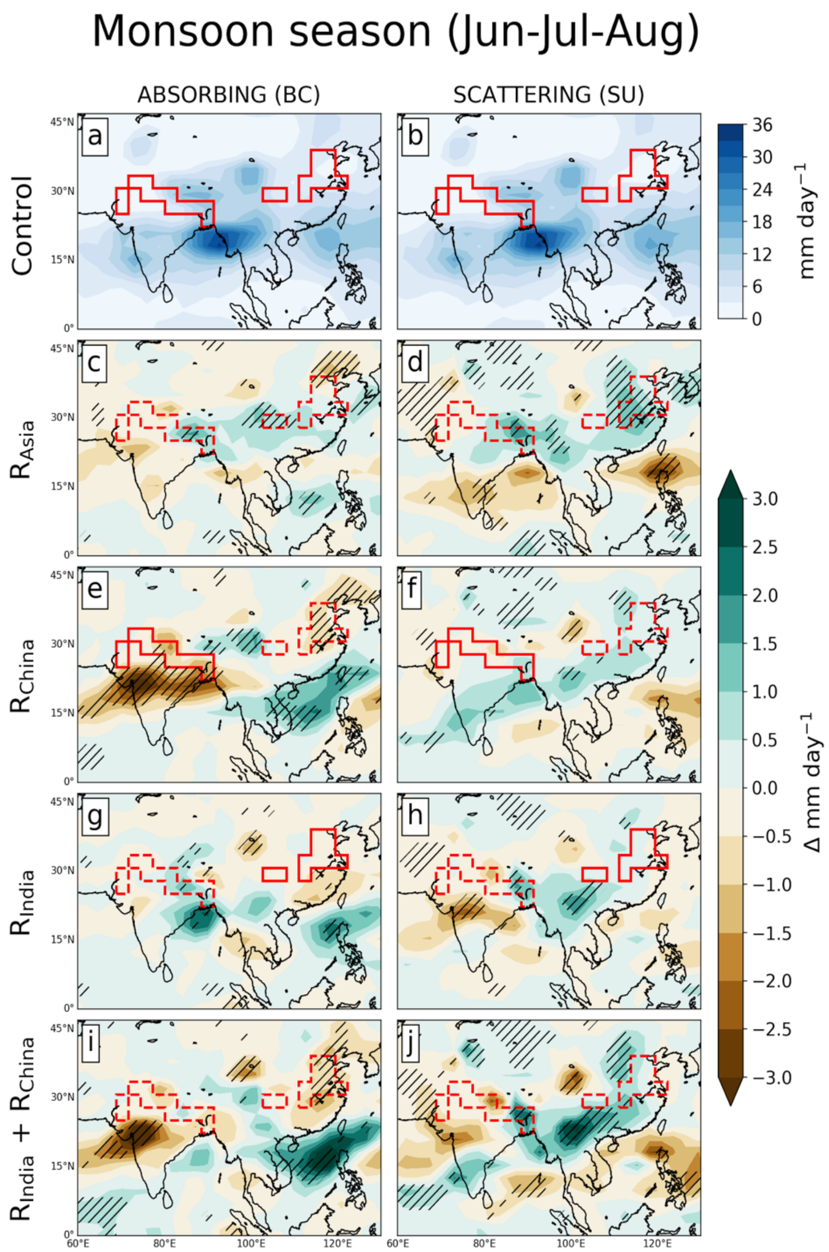

Figure 4. As figure 3 but for the monsoon season (June, July, August). A version showing percentage change in precipitation is shown in figure S3.

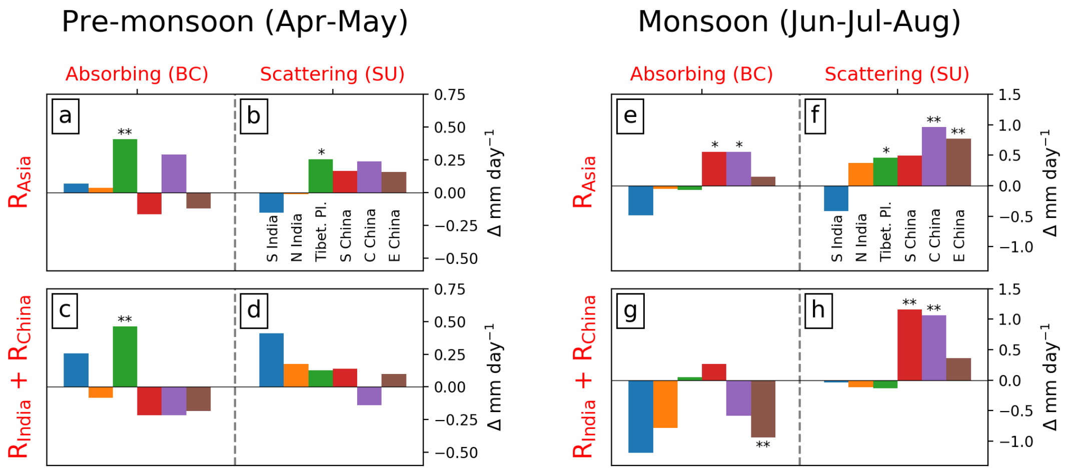

Figure 5. Examining the non-linearity of the emission reduction pathway. Regional mean precipitation response to the reduction of anthropogenic aerosol over Asia in the pre-monsoon (**a** – **d**) and the monsoon (**e** – **h**) seasons. The top row shows the response from the reduction throughout Asia (India and China), and the bottom row shows the combined response from independent reductions over India and China. A statistically significant change at 90% (95%) confidence in a region is indicated by * (**) above the bar. Please note the different ranges used for each season.

Supplementary information for manuscript: "Nonlinear Response of Asian Summer Monsoon Precipitation to Emission Reductions in India and China"

The supplementary material consists of three figures (figures S1, S2, and S3) and one table (table S1).

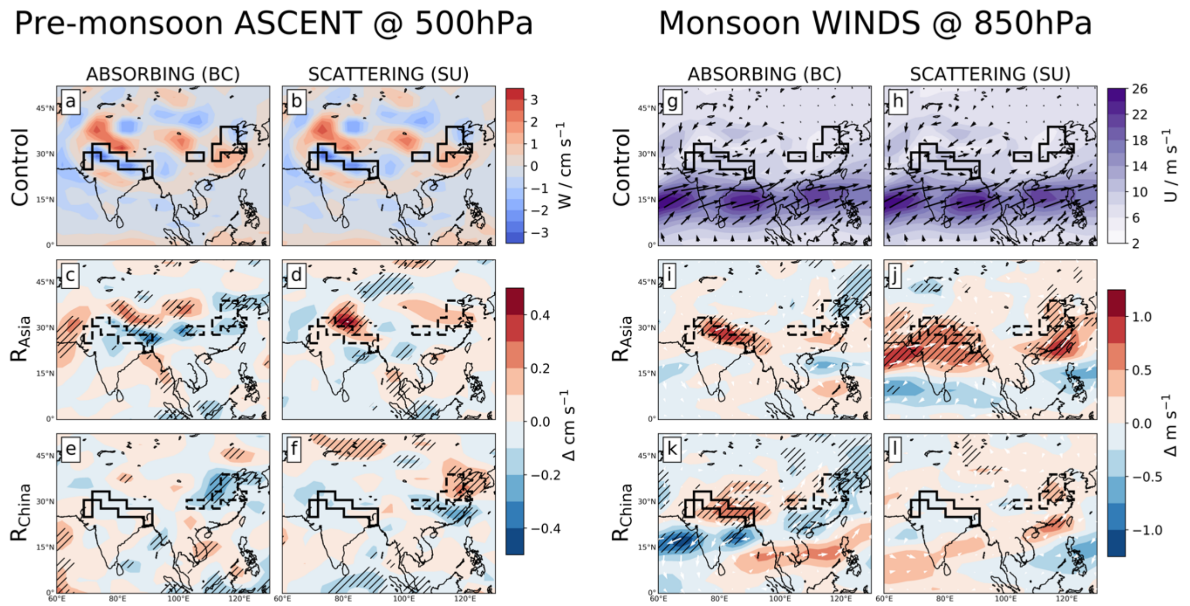

Figure S1. Effects on large-scale dynamics and circulation: pre-monsoon vertical ascent at 500 hPa (**a** – **f**) and monsoon horizontal winds at 850 hPa (**g** – **l**). The top row shows the seasonal mean in present day simulations (**a** – **b, g** – **h**), and the seasonal mean response due to aerosol reductions in experiments R_{Asia} (**c** – **d, i** – **j**) and R_{China} (**e** – **f, k** – **l**). Within each dataset the left-hand column is for absorbing aerosol and the right-hand column is for scattering aerosol. Hatched areas show a statistically significant change at or above a confidence of 90%. Solid black boxes show the location of the regional perturbation, and dashed boxes where the perturbation has been removed. For panels **i** – **l** white arrows show the anomalous meridional and zonal wind components, and contours show the absolute change in wind speed.

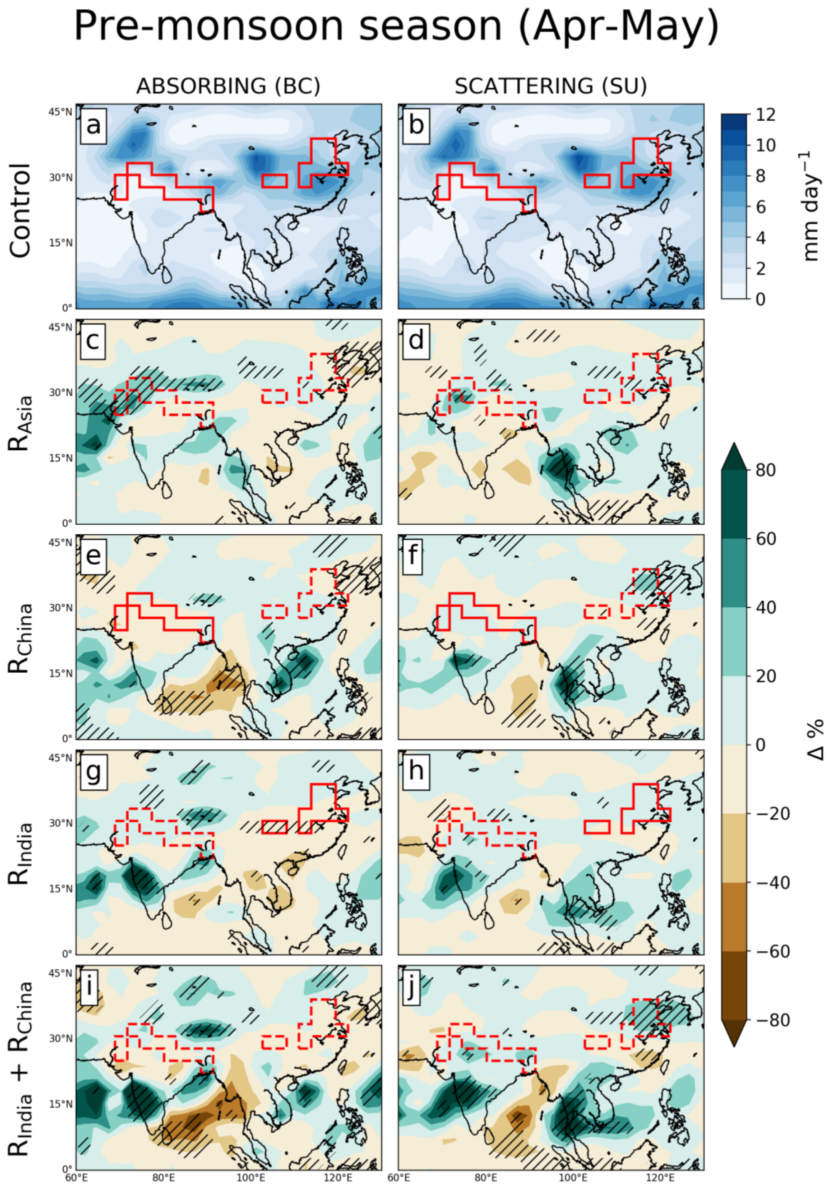

Figure S2. Pre-monsoon (April and May) seasonal mean precipitation rate in present day simulations (**a** – **b**), and the percentage change due to aerosol reductions in experiments R_{Asia} (**c** – **d**), R_{China} (**e** – **f**), R_{India} (**g** – **h**), and the summed contribution R_{China}+R_{India} (**i** – **j**). The column on the left is for absorbing (BC) aerosol and the column on the right is for scattering (SU) aerosol. Hatched areas show a statistically significant change at or above a confidence of 90%. Solid red boxes show the location of the regional perturbation, and dashed boxes where the perturbation has been removed.

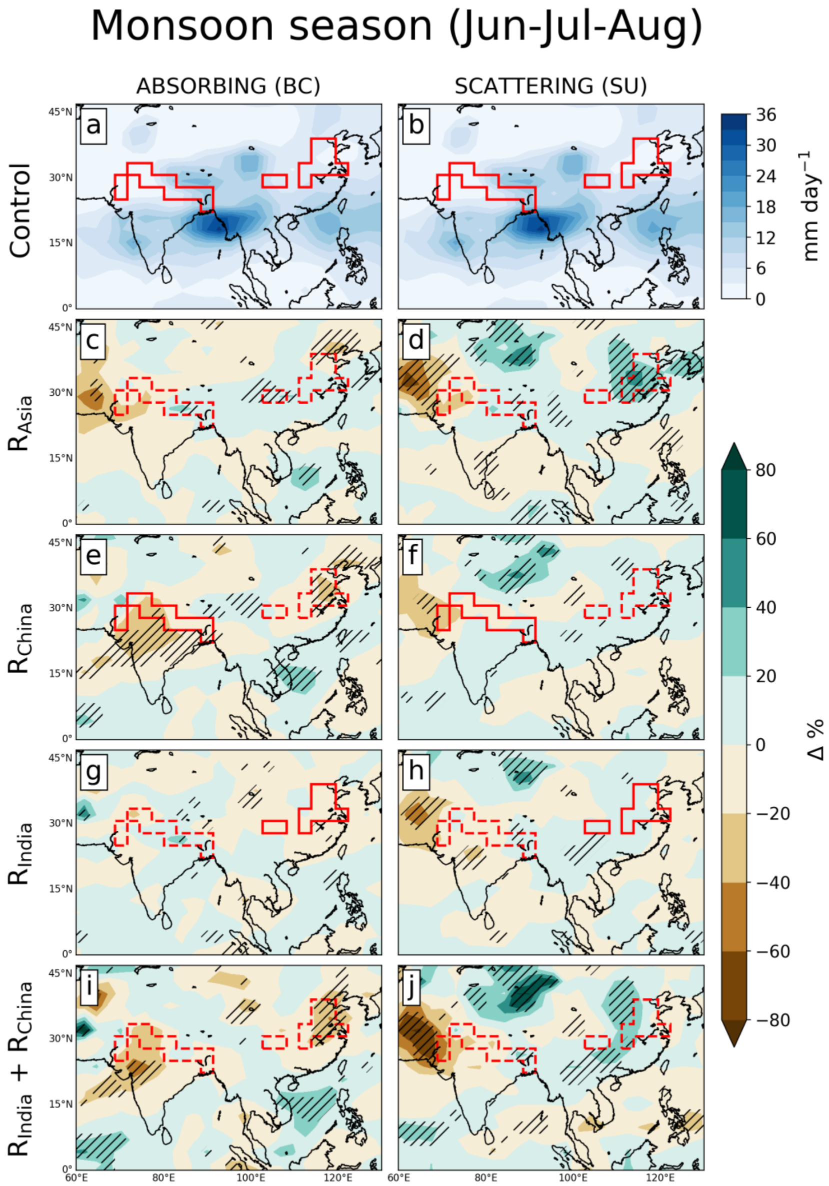

Figure S3. As figure S2 but for the monsoon season.

	Pre-monsoon season			Monsoon season	
	Absorbing	**Scattering**		**Absorbing**	**Scattering**
South India	0.1 (0.3)	-0.2 (0.4)		-0.5 (-1.2)	-0.4 (0.0)
North India	0.0 (-0.1)	0.0 (0.2)		0.0 (-0.8)	0.4 (-0.1)
Tibetan Plateau	0.4 (0.5)	0.3 (0.1)		-0.1 (0.0)	0.5 (-0.1)
South China	-0.2 (-0.2)	0.2 (0.1)		0.6 (0.3)	0.5 (1.2)
Central China	0.3 (-0.2)	0.2 (-0.1)		0.6 (-0.6)	1.0 (1.1)
East China	-0.1 (-0.2)	0.2 (0.1)		0.2 (-0.9)	0.8 (0.4)

Table S1. Data as shown in figure 5 of the manuscript. Values show the mean precipitation response (mm day^{-1}) in each season, and for each region, for R_{Asia} simulations with either BC or SU aerosol. Data in brackets are for the summed response $R_{China}+R_{India}$.