Nonlinear Response of Asian Summer Monsoon Precipitation to Emission Reductions in South and East Asia

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 uncertainties such as timescale, location, or emission type. We use a circulation/climate model with idealised aerosol distributions to demonstrate that the sum of ASM responses to 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 results from interaction of induced atmospheric circulation changes. The nonlinearity from interactions between aerosol forcing from different regions represents a new source of uncertainty in projections of ASM changes over the next 30-40 years, and may limit the utility of country-dependent aerosol trajectories when considering their Asia-wide effects, though we recommend further work to establish whether the nonlinearity is buffered by other drivers. 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 such as India and China 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 [1,2] 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 [1,3–6]. 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 [1,4,7–10], though other factors such as warming of the surrounding oceans [11,12] and changes to land-surface properties [13] may play a secondary role. Recent years have seen a revival of the South Asian branch of the ASM occurring alongside increasing local aerosol emissions [14,15], which highlights remaining uncertainty in the drivers of ASM changes and a potential role for non-local aerosol emissions in the northern hemisphere (e.g., [16]).

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 [6,17,18].

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 [19–21], 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 [22–25]. Although the instantaneous responses to SU and BC are different the net response to aerosol is an overall weakening of the ASM driven by the surface cooling that both species exert [26].

Most future changes in Asian anthropogenic aerosol emissions will occur in South and East Asia, 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 [18,27,28]. 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 [29,30].

In this study we focus on how projected future aerosol reductions in South and East Asia will impact the ASM. We achieve this by exploring the climate response to regional aerosol removal over South and East Asia, 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) [31], which has been previously used for studies related to climate, aerosol, and tropical meteorology [32–38] and reproduces the observed timing and magnitude of the ASM (figure 1), a feat many CMIP6 models are unable to replicate [6]. Here we employ a monthly-varying sea-surface temperature climatology and observationally constrained idealized aerosol perturbations over South and East Asia. 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 [39]. An evaluation [31] 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 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., [40,41]), which are reflected in large differences in the magnitude and pattern of anthropogenic aerosol radiative forcing in CMIP6 [6], 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 determine the geographical location of the largest aerosol burdens over South and East Asia. For South Asia the spatial patterns are largely determined by the geography, with aerosol accumulating over the Indo Gangetic Plain along the slopes of the Himalayas. In East Asia aerosol is well correlated with regions of heavy industry across China, including the North China Plain and Yangtze River Delta to the east and

Sichuan Basin to the west. Figure 2b demonstrates that we capture these key anomalies.

Idealized vertical profiles for the anthropogenic aerosol are based on observations from each region: in South Asia the simulated aerosol extends from the surface up to 600 hPa or 3.5 km [42–45]; and in East Asia the aerosol extends from the surface to 800 hPa or 2 km [46,47]. 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 South Asia the AOD increases throughout the spring then rapidly decreases as the monsoon precipitation enhances scavenging processes. In East Asia the industrial regions are less impacted by monsoon precipitation, and sustain enhanced AOD throughout the monsoon season. We note that the AOD observations implicitly include natural aerosol sources such as dust from the Arabian peninsula and sea salt from the surrounding oceans. In our simulations we do not treat aerosol species separately and instead assume that all AOD comes from these simple approximations of anthropogenic aerosol, which represents the greater source of future forcing uncertainty.

2.2 Experiments

We perform a total of eight simulations run for 50 years (see Table 1). In our control simulations we use present-day aerosol concentrations and spatial distributions over both South and East Asia as shown in figure 2. Given the uncertainty in aerosol properties and how they will change in time we perform separate control simulations for scattering (SU) and absorbing (BC). To examine the impact of aerosol emission reductions we remove the present-day aerosol from either one region only, or both simultaneously. By comparing to the control simulations we can quantify the climate response to aerosol removal over South Asia only ($R_{South\ Asia}$), East Asia only ($R_{East\ Asia}$), and over both regions simultaneously (R_{Asia}). The aerosol removal experiments are repeated for both BC and SU aerosol properties. By summing the climate response in the individual removal experiments ($R_{South\ Asia}$ + $R_{East\ Asia}$) and comparing to R_{Asia} we are able to quantify nonlinear behaviour in the response to regional emission reduction pathways. Contrasting the BC and SU experiments can inform us about the dependence of the nonlinearity on the aerosol species. 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. The statistical significance of the climate response in each experiment is determined using a students t-test applied to the gridded seasonal means, providing 40 samples at each grid point from each experiment.

3. Results

3.1 Pre-monsoon season

Simulated present-day precipitation during the pre-monsoon (figures 3a) 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 precipitation over the Tibetan Plateau (TP) (figures 3b, 3c); BC removal produces a stronger response (up to +40%) than SU (up to +20%) and additionally causes robust drying over NE Asia and the NW Pacific Ocean by -20%. Significant responses are largely confined to latitudes between 25° N and 40° N, with 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 (BC removal produces anomalous cooling aloft) or promotion (SU removal enhances surface warming) of localized ascent and the subsequent redirection of air flow downstream. In South Asia both aerosol species enhance flow over the Himalayas and across the TP (via contrasting mechanisms; see supplementary information), enhancing the transport of moisture and precipitation to the region, whilst weakening flow down the IGP into central and S China. Over East Asia the aerosol directly modifies localized regions of ascent and descent.

Removing aerosol in East Asia alone ($R_{East\ Asia}$) prevents the increase in pre-monsoon precipitation over the Tibetan Plateau (figures 3d**,** 3e) that is observed in the R_{Asia} experiment, but now we observe a robust reduction in precipitation over the Bay of Bengal by up to -40%. The removal of BC and SU over East Asia alone exerts a relatively stronger local effect on the atmospheric circulation than when removed alongside South Asian aerosol (see figure S4) 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 regions of 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 3b, 3c), yet the summed response from $R_{South\ Asia}$ + $R_{East\ Asia}$ (figures 3h, 3i) 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 East Asia (figure 3i) is also absent in the R_{Asia} experiment (figure 3c).

3.2 Monsoon season

During the monsoon season (figure 4) aerosol removal in R_{Asia} generally results in enhanced precipitation (up to +20% for BC; +40% for SU) across much of China with isolated regions of significant drying up to -20% to the south, most notably over S India and the SW Pacific Ocean. The removal of SU produces anomalous warming of the boundary layer and associated ascent. Over South Asia westerly flow down the IGP is enhanced, whilst over East Asia widespread anomalous low pressure and an enhanced meridional temperature gradient produces a pronounced northward shift and strengthening of the low-level jet over Asia, with an enhanced northerly component over E China. The combined mechanisms drive the observed dipole in precipitation response. The removal 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 removal is consistent with other studies [6,48,49] 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 removal of BC aerosol in East Asia alone (figure 4d) 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 removal is stronger when reduced in East Asia alone. SU removal from East Asia alone (figure 4e) shows a similar spatial pattern to R_{Asia} but the dipole in precipitation response is weaker and less significant (over China R_{Asia} = +40%; $R_{East\ Asia}$ = +20%). The warming that is induced by the removal of SU over East Asia is sufficient to impact the jet position but the effect is considerably enhanced when both South and East Asian aerosol is removed simultaneously; this result is consistent with a recent analysis of earth-system models [49].

Similar to the pre-monsoon season there exist regions of robust nonlinearity in the monsoon precipitation response from aerosol removal in South and East Asia. The starkest contrast between R_{Asia} (figures 4b, 4c) and $R_{South\ Asia} + R_{East\ Asia}$ (figures 4h, 4i) 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 East Asia produces significant drying over India (figure 4d) yet when aerosols are removed in both regions simultaneously this is entirely suppressed (figure 4b); a similar response occurs over the SW Pacific and South China Sea. India and S China 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 S4). It is worth noting that there is variability in the regional precipitation response throughout the monsoon season (figures S9 and S10) for both aerosol species, likely driven by intra-seasonal variability in the monsoon progression; despite this, nonlinearity is evident in all cases.

Additional information on the mechanisms driving the observed responses in both seasons, including cross sections of the temperature and wind response, is presented in the supplementary imformation.

4. Discussion

Figure 5 summarises the degree of nonlinearity in the ASM to regional aerosol forcing (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 removed in both regions together, especially during the monsoon season when robust signals in the position of the low-level jet response are evident (figure S11). The nonlinearity is generally stronger for BC aerosol; absorbing aerosol perturbations in both regions cause heating aloft and have strong influence on the flow over the Tibetan Plateau which directly links the two regions. These circulation anomalies compete when aerosol is changed in both regions together which implies that the ability to predict aerosol composition in the future (proportions of BC and SU) will not remove the nonlinearity. The analysis suggests that the south of India is particularly sensitive to nonlinearity (figure S11).

Whilst the spatial distribution of statistically significant precipitation response (figures 3 and 4) and nonlinearity (figure S11) represents a relatively small fraction of the gridpoints, aggregating the data regionally in figure 5 supports significant changes and helps identify particularly sensitive regions. In the pre-monsoon season the Tibetan Plateau is the only region to exhibit a significant precipitation response, whereas in the monsoon season significant responses are evident throughout East Asia. The lack of significant responses over South Asia can be explained by the pronounced intra-seasonal variability over the region (figure S10).

Current trends show a decreasing SU burden over East Asia. Our simulations suggest this will increase monsoon precipitation, though if SU emissions were concurrently reduced over South Asia 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 [4,50], which may counteract the drying we observe in S India. BC removal over East Asia in isolation will produce widespread cooling which weakens the monsoon circulation, especially over India, whereas BC removal in both South and East Asia suppresses the response and results in enhanced precipitation across much of Asia.

The nonlinearity from interactions between responses to regional forcing 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 [49]. However, the regions of 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 [6], 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 [4,5,21,51,52]. 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. The role of the sea-surface temperature response on decadal timescales has also been found to be an important driver of the monsoon response to aerosol, especially from ACI over the Pacific Ocean [8]. On shorter timescales, aerosol can amplify the monsoon response to ENSO [53] and precipitation and circulation responses may feedback on natural aerosol emissions, adding further complexity to regional projections. It is possible that the nonlinearity we observe may be buffered or enhanced when complexity is increased, therefore future work should examine how the nonlinearity is affected by other drivers including the roles of increasing GHG concentrations, coupled oceans, and fully interactive aerosol (including both natural and anthropogenic sources). The latter would permit the treatment of ACI processes which are omitted in this study; although ACI will likely impact the magnitude and pattern of the responses we simulate, the nonlinearity we observe is driven by widespread changes to the atmospheric circulation over South and East Asia which are unlikely to be dampened to an extent that our conclusions would not remain, but should be considered in future studies. 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 [54] 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.

Acknowledgements

RJH and EH acknowledge funding by the UK Natural Environment Research Council (NERC) project SWAAMI (NE/L013886/1). MJ acknowledges funding from the NERC projects EMERGENCE (NE/S004645/1) and BoBBLE (NE/L013827/1). LJW was supported by the NERC projects EMERGENCE (NE/S004645/1) and SWAAMI (NE/L013886/1). DJF was supported by the Endeavour Fund *Whakahura* programme.

All simulated data and scripts necessary for reproducing the plots in this manuscript are available from http://doi.org/10.5281/zenodo.4639423.

References

[1] Lau W K-M and Kim K-M 2017 Competing influences of greenhouse warming and aerosols on Asian summer monsoon circulation and rainfall *Asia-Pacific J Atmos Sci* **53** 181–94

[2] Sutton R T, Dong B and Gregory J M 2007 Land/sea warming ratio in response to climate change: IPCC

AR4 model results and comparison with observations *Geophysical Research Letters* **34**

[3] Polson D, Bollasina M, Hegerl G C and Wilcox L J 2014 Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols *Geophysical Research Letters* **41** 6023–9

[4] Song F, Zhou T and Qian Y 2014 Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models *Geophysical Research Letters* **41** 596–603

[5] Undorf S, Polson D, Bollasina M A, Ming Y, Schurer A and Hegerl G C 2018 Detectable Impact of Local and Remote Anthropogenic Aerosols on the 20th Century Changes of West African and South Asian Monsoon Precipitation *Journal of Geophysical Research: Atmospheres* **123** 4871–89

[6] Wilcox L J, Liu Z, Samset B H, Hawkins E, Lund M T, Nordling K, Undorf S, Bollasina M, Ekman A M L, Krishnan S, Merikanto J and Turner A G 2020 Accelerated increases in global and Asian summer monsoon precipitation from future aerosol reductions *Atmospheric Chemistry and Physics* **20** 11955–77

[7] Bollasina M A, Ming Y and Ramaswamy V 2011 Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon *Science* **334** 502–5

[8] Dong B, Wilcox L J, Highwood E J and Sutton R T 2019 Impacts of recent decadal changes in Asian aerosols on the East Asian summer monsoon: roles of aerosol–radiation and aerosol–cloud interactions *Clim Dyn* **53** 3235–56

[9] Li X, Ting M, Li C and Henderson N 2015 Mechanisms of Asian Summer Monsoon Changes in Response to Anthropogenic Forcing in CMIP5 Models *Journal of Climate* **28** 4107–25

[10] Liu Z, Ming Y, Wang L, Bollasina M, Luo M, Lau N-C and Yim S H-L 2019 A Model Investigation of Aerosol-Induced Changes in the East Asian Winter Monsoon *Geophysical Research Letters* **46** 10186–95

[11] Rao S A, Chaudhari H S, Pokhrel S and Goswami B N 2010 Unusual Central Indian Drought of Summer Monsoon 2008: Role of Southern Tropical Indian Ocean Warming *Journal of Climate* **23** 5163–74

[12] Roxy M K, Ritika K, Terray P, Murtugudde R, Ashok K and Goswami B N 2015 Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient *Nat Commun* **6** 7423

[13] Paul S, Ghosh S, Oglesby R, Pathak A, Chandrasekharan A and Ramsankaran R 2016 Weakening of Indian Summer Monsoon Rainfall due to Changes in Land Use Land Cover *Sci Rep* **6** 32177

[14] Hari V, Villarini G, Karmakar S, Wilcox L J and Collins M 2020 Northward Propagation of the Intertropical Convergence Zone and Strengthening of Indian Summer Monsoon Rainfall *Geophysical Research Letters* **47** e2020GL089823

[15] Jin Q and Wang C 2017 A revival of Indian summer monsoon rainfall since 2002 *Nature Clim Change* **7** 587–94

[16] Undorf S, Bollasina M A and Hegerl G C 2018 Impacts of the 1900–74 Increase in Anthropogenic Aerosol Emissions from North America and Europe on Eurasian Summer Climate *Journal of Climate* **31** 8381–99

[17] Bartlett R E, Bollasina M A, Booth B B B, Dunstone N J, Marenco F, Messori G and Bernie D J 2018 Do differences in future sulfate emission pathways matter for near-term climate? A case study for the Asian monsoon *Clim Dyn* **50** 1863–80

[18] Samset B H, Lund M T, Bollasina M, Myhre G and Wilcox L 2019 Emerging Asian aerosol patterns *Nature Geoscience* **12** 582–4

[19] Westervelt D M, You Y, Li X, Ting M, Lee D E and Ming Y 2020 Relative Importance of Greenhouse Gases, Sulfate, Organic Carbon, and Black Carbon Aerosol for South Asian Monsoon Rainfall Changes *Geophysical Research Letters* **47** e2020GL088363

[20] Kim M J, Yeh S-W and Park R J 2016 Effects of sulfate aerosol forcing on East Asian summer monsoon for 1985–2010 *Geophysical Research Letters* **43** 1364–72

[21] Dong B, Sutton R T, Highwood E J and Wilcox L J 2016 Preferred response of the East Asian summer monsoon to local and non-local anthropogenic sulphur dioxide emissions *Clim Dyn* **46** 1733–51

[22] Collier J C and Zhang G J 2009 Aerosol direct forcing of the summer Indian monsoon as simulated by the NCAR CAM3 *Clim Dyn* **32** 313–32

[23] Lau K M, Kim M K and Kim K M 2006 Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau *Clim Dyn* **26** 855–64

[24] Meehl G A, Arblaster J M and Collins W D 2008 Effects of Black Carbon Aerosols on the Indian Monsoon *Journal of Climate* **21** 2869–82

[25] Menon S, Hansen J, Nazarenko L and Luo Y 2002 Climate Effects of Black Carbon Aerosols in China and India *Science* **297** 2250–3

[26] Persad G G, Paynter D J, Ming Y and Ramaswamy V 2017 Competing Atmospheric and Surface-Driven Impacts of Absorbing Aerosols on the East Asian Summertime Climate *Journal of Climate* **30** 8929–49

[27] Lund M T, Myhre G and Samset B H 2019 Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways *Atmospheric Chemistry and Physics* **19** 13827–39

[28] Riahi K, van Vuuren D P, Kriegler E, Edmonds J, O'Neill B C, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma J C, Kc S, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva L A, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman J C, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A and Tavoni M 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview *Global Environmental Change* **42** 153–68

[29] Li C, McLinden C, Fioletov V, Krotkov N, Carn S, Joiner J, Streets D, He H, Ren X, Li Z and Dickerson R R 2017 India Is Overtaking China as the World's Largest Emitter of Anthropogenic Sulfur Dioxide *Sci Rep* **7** 14304

[30] Zheng B, Tong D, Li M, Liu F, Hong C, Geng G, Li H, Li X, Peng L, Qi J, Yan L, Zhang Y, Zhao H, Zheng Y, He K and Zhang Q 2018 Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions *Atmospheric Chemistry and Physics* **18** 14095–111

[31] Joshi M, Stringer M, van der Wiel K, O'Callaghan A and Fueglistaler S 2015 IGCM4: a fast, parallel and flexible intermediate climate model *Geoscientific Model Development* **8** 1157–67

[32] Joshi M, Shine K, Ponater M, Stuber N, Sausen R and Li L 2003 A comparison of climate response to different radiative forcings in three general circulation models: towards an improved metric of climate change *Climate Dynamics* **20** 843–54

[33] Cnossen I, Lu H, Bell C J, Gray L J and Joshi M M 2011 Solar signal propagation: The role of gravity waves and stratospheric sudden warmings *Journal of Geophysical Research: Atmospheres* **116**

[34] Shine K P, Cook J, Highwood E J and Joshi M M 2003 An alternative to radiative forcing for estimating the relative importance of climate change mechanisms *Geophysical Research Letters* **30**

[35] van der Wiel K, Matthews A J, Joshi M M and Stevens D P 2016 Why the South Pacific Convergence Zone is diagonal *Clim Dyn* **46** 1683–98

[36] Ratna S B, Osborn T J, Joshi M and Luterbacher J 2020 The Influence of Atlantic Variability on Asian Summer Climate Is Sensitive to the Pattern of the Sea Surface Temperature Anomaly *Journal of Climate* **33** 7567–90

[37] Ratna S B, Cherchi A, Osborn T J, Joshi M and Uppara U 2021 The Extreme Positive Indian Ocean Dipole of 2019 and Associated Indian Summer Monsoon Rainfall Response *Geophysical Research Letters* **48** e2020GL091497

[38] Ferraro A J, Charlton-Perez A J and Highwood E J 2015 Stratospheric dynamics and midlatitude jets under geoengineering with space mirrors and sulfate and titania aerosols *Journal of Geophysical Research: Atmospheres* **120** 414–29

[39] Reynolds R W, Rayner N A, Smith T M, Stokes D C and Wang W 2002 An Improved In Situ and Satellite SST Analysis for Climate *Journal of Climate* **15** 1609–25

[40] Rothenberg D, Avramov A and Wang C 2018 On the representation of aerosol activation and its influence on model-derived estimates of the aerosol indirect effect *Atmospheric Chemistry and Physics* **18** 7961–83

[41] Simpson E, Connolly P and McFiggans G 2014 An investigation into the performance of four cloud droplet activation parameterisations *Geoscientific Model Development* **7** 1535–42

[42] Sarangi C, Tripathi S N, Mishra A K, Goel A and Welton E J 2016 Elevated aerosol layers and their radiative impact over Kanpur during monsoon onset period *Journal of Geophysical Research: Atmospheres* **121** 7936–57

[43] Brooks J, Allan J D, Williams P I, Liu D, Fox C, Haywood J, Langridge J M, Highwood E J, Kompalli S K, O'Sullivan D, Babu S S, Satheesh S K, Turner A G and Coe H 2019 Vertical and horizontal distribution

of submicron aerosol chemical composition and physical characteristics across northern India during pre-monsoon and monsoon seasons *Atmospheric Chemistry and Physics* **19** 5615–34

[44] Gautam R, Hsu N C and Lau K-M 2010 Premonsoon aerosol characterization and radiative effects over the Indo-Gangetic Plains: Implications for regional climate warming *Journal of Geophysical Research: Atmospheres* **115**

[45] Nair V S, Babu S S, Gogoi M M and Moorthy K K 2016 Large-scale enhancement in aerosol absorption in the lower free troposphere over continental India during spring *Geophysical Research Letters* **43** 11,453-11,461

[46] Tian P, Cao X, Zhang L, Sun N, Sun L, Logan T, Shi J, Wang Y, Ji Y, Lin Y, Huang Z, Zhou T, Shi Y and Zhang R 2017 Aerosol vertical distribution and optical properties over China from long-term satellite and ground-based remote sensing *Atmospheric Chemistry and Physics* **17** 2509–23

[47] de Leeuw G, Sogacheva L, Rodriguez E, Kourtidis K, Georgoulias A K, Alexandri G, Amiridis V, Proestakis E, Marinou E, Xue Y and van der A R 2018 Two decades of satellite observations of AOD over mainland China using ATSR-2, AATSR and MODIS/Terra: data set evaluation and large-scale patterns *Atmospheric Chemistry and Physics* **18** 1573–92

[48] Samset B H, Myhre G, Forster P M, Hodnebrog Ø, Andrews T, Faluvegi G, Fläschner D, Kasoar M, Kharin V, Kirkevåg A, Lamarque J-F, Olivié D, Richardson T, Shindell D, Shine K P, Takemura T and Voulgarakis A 2016 Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study *Geophysical Research Letters* **43** 2782–91

[49] Sherman P, Gao M, Song S, Archibald A T, Abraham N L, Lamarque J-F, Shindell D, Faluvegi G and McElroy M B 2021 Sensitivity of modeled Indian monsoon to Chinese and Indian aerosol emissions *Atmospheric Chemistry and Physics* **21** 3593–605

[50] Chen G, Wang W-C and Chen J-P 2018 Circulation responses to regional aerosol climate forcing in summer over East Asia *Clim Dyn* **51** 3973–84

[51] Wang Z, Lin L, Yang M, Xu Y and Li J 2017 Disentangling fast and slow responses of the East Asian summer monsoon to reflecting and absorbing aerosol forcings *Atmospheric Chemistry and Physics* **17** 11075–88

[52] Guo L, Turner A G and Highwood E J 2016 Local and Remote Impacts of Aerosol Species on Indian Summer Monsoon Rainfall in a GCM *Journal of Climate* **29** 6937–55

[53] Kim M-K, Lau W K M, Kim K-M, Sang J, Kim Y-H and Lee W-S 2016 Amplification of ENSO effects on Indian summer monsoon by absorbing aerosols *Clim Dyn* **46** 2657–71

[54] Kaul I 2003 *Providing Global Public Goods: Managing Globalization* (New York: Oxford University Press)

Tables

Experiment*	Aerosol distribution	Experiment purpose
Control	Present-day aerosol over South and East Asia	Control experiment (either BC or SU)
$R_{East\ Asia}$	Aerosol only present over South Asia	Climate response to removal of aerosol over East Asia
$R_{South\ Asia}$	Aerosol only present over East Asia	Climate response to removal of aerosol over South Asia
R_{Asia}	No aerosol	Climate response to removal of aerosol over both South and East Asia

* Each experiment is repeated for either strongly absorbing BC-like aerosol (BC) or strongly scattering sulphate-like aerosol (SU)

Figures

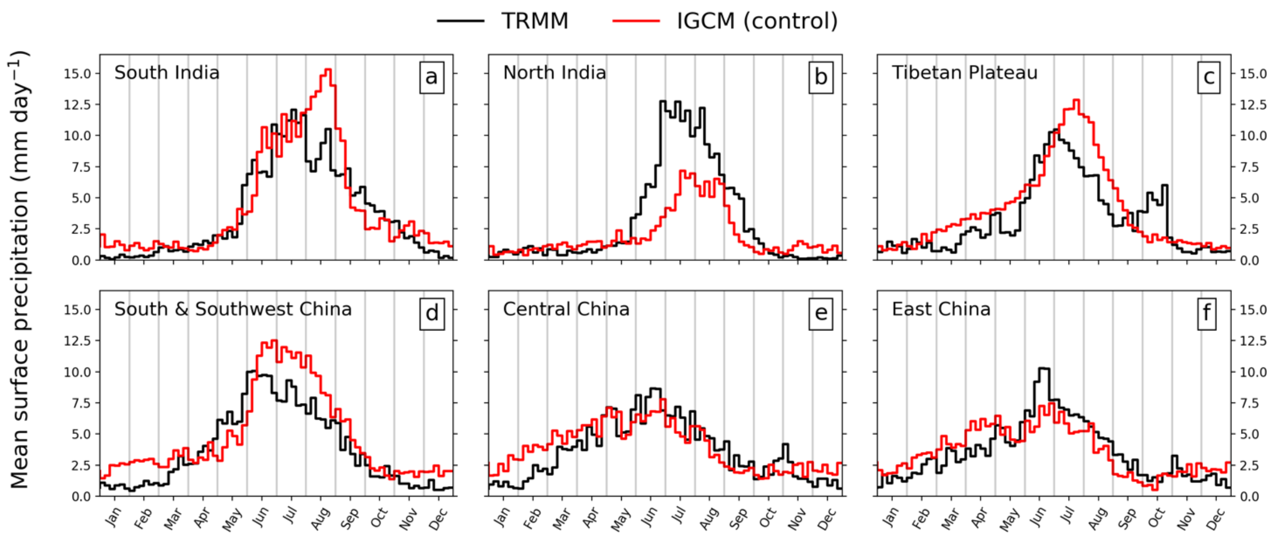

Figure 1. Comparison of simulated mean annual surface precipitation rates with satellite observations from the Tropical Rainfall Measuring Mission Project (TRMM) over six regions in Asia. Simulated data (red line) is shown for the present-day experiment with sulphate aerosol. Daily TRMM data from 2000 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.

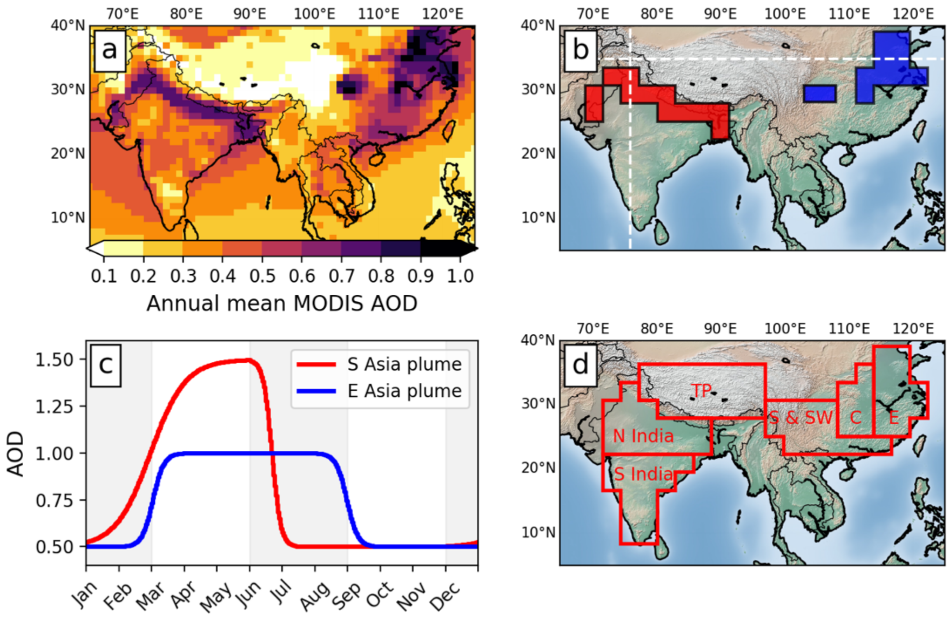

Figure 2. Experimental setup showing: (a) MODIS annual mean AOD climatology (2001-2020); (b) spatial distribution of the simulated aerosol plumes; (c) annual cycle of the AOD for the two regions; and (d) geographical locations of each region used for the analysis of regional precipitation responses shown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

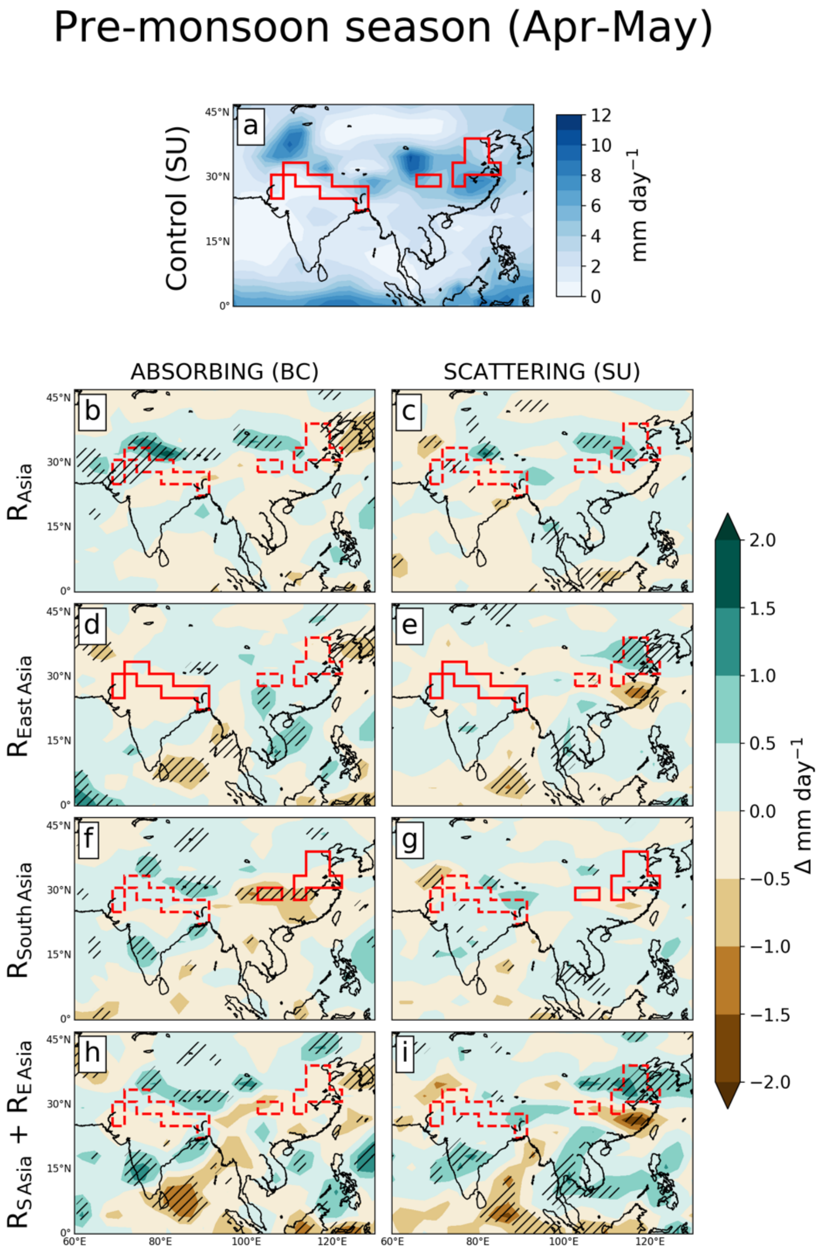

Figure 3. Pre-monsoon (April and May) seasonal mean precipitation rate in the present day (a), and the absolute response due to aerosol reductions in experiments R_{Asia} (b – c), $R_{East\ Asia}$ (d – e), $R_{South\ Asia}$ (f – g), and the summed contribution $R_{South\ Asia}$+$R_{East\ Asia}$ (h – i). 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 S7. Note that for clarity the present-day control simulation (a) is only shown for SU aerosol.

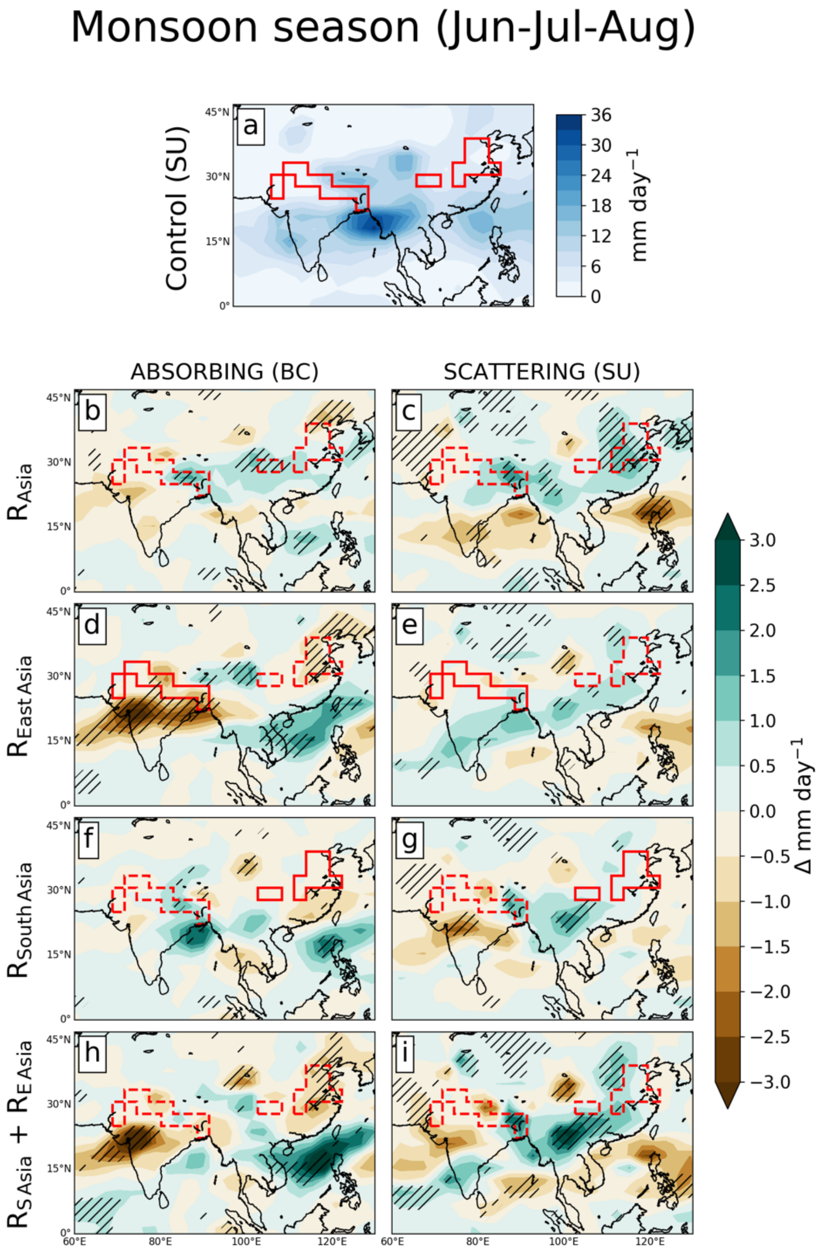

Figure 4. As figure 3 but for the monsoon season (June, July, August). A version showing percentage change in precipitation is shown in figure S8.

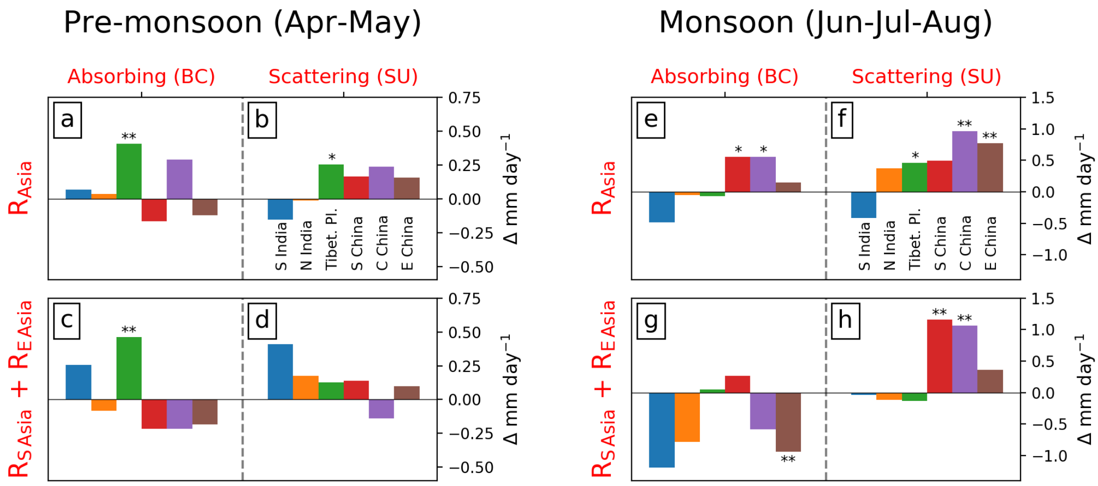

Figure 5. Examining the non-linearity of the emission reduction pathway. Regional mean precipitation response to the reduction of anthropogenic aerosol over Asia in the pre-monsoon (**a** – **d**) and the monsoon (**e** – **h**) seasons. The top row shows the response from the reduction throughout Asia (South and East Asia), and the bottom row shows the combined response from independent reductions over the two regions. 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.