The South Asian Monsoon Response to Remote Aerosols: Global and Regional Mechanisms

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Abstract The South Asian summer monsoon has been suggested to be influenced by atmospheric aerosols, and this influence can be the result of either local or remote emissions. We have used the Hadley Centre Global Environment Model Version 3 (HadGEM3) coupled atmosphere-ocean climate model to investigate for the first time the centennial-scale South Asian precipitation response to emissions of sulfur dioxide (SO2), the dominant anthropogenic precursor of sulfate aerosol, from different midlatitude regions. Despite the localized nature of the regional heating that results from removing SO2 emissions, all experiments featured a similar large-scale precipitation response over South Asia, driven by ocean-modulated changes in the net cross-equatorial heat transport and an opposing cross-equatorial northward moisture transport. The effects are linearly additive, with the sum of the responses from the experiments where SO2 is removed from the United States, Europe, and East Asia resembling the response seen in the experiment where emissions are removed from the northern midlatitudes as a whole, but with East Asia being the largest contributor, even per unit of emission or top-of-atmosphere radiative forcing. This stems from the fact that East Asian emissions can more easily influence regional land-sea thermal contrasts and sea level pressure differences that drive the monsoon circulation, compared to emissions from more remote regions. Our results suggest that radiative effects of remote pollution should not be neglected when examining changes in South Asian climate and that it is important to examine such effects in coupled ocean-atmosphere modeling frameworks.

Plain Language Summary Atmospheric aerosols have been shown to exert a strong influence on global and regional climate through their radiative effects. The South Asian summer monsoon, a climate phenomenon on which billions of lives depend, has been suggested to be influenced by aerosols, and this influence can be the result of either local or remote emissions. We have used a global climate model to investigate how sensitive is the monsoon to emissions from remote industrialized regions such as Europe, the North America, and East Asia. Despite the localized nature of the regional heating that results from removing emissions in these regions, all of them featured a similar large-scale rainfall change remotely over South Asia. This similarity reflects a common underlying mechanism, which involves a displacement of the tropical rain belt driven by aerosol effects on the temperature contrast between the two hemispheres of the Earth. We find that the effects of the different regions on South Asia are linearly additive, with East Asia being the largest contributor. This stems from the fact that its emissions can more easily influence regional land-sea thermal contrasts and sea level pressure differences over Asia that drive the summer monsoon circulation, compared to emissions from more remote regions. Our results suggest that influences of remote pollution should not be neglected when examining changes in South Asian climate and can help inform policy on the co-benefits and side effects of ongoing strategies that control regional air pollution in extratropical regions.

1. Introduction

The livelihoods of over a billion people in South Asia rely on the summer monsoon. The monsoon system dominates the climate of South Asia, bringing 80% of the annual rainfall to the region during the summer season (Guo et al., 2016; Ramanathan et al., 2005). The monsoon can be viewed as the seasonal migration of the Intertropical Convergence Zone (ITCZ; Privé & Plumb, 2007). The position of the ITCZ is largely determined by the interhemispheric temperature gradient upon which the monsoon system functions (Guo et al., 2015). The rainfall brought by the monsoon has been decreasing during the late twentieth century (Krishnan et al., 2016), likely due to increases in anthropogenic aerosols (Bollasina et al., 2011; Ramanathan et al., 2005). It is important that we understand the interactions between pollution and monsoon rainfall, particularly the
impacts of aerosols whose short lifetime in the atmosphere means that they impose an inhomogeneous radiative forcing in different parts of the globe. This spatially unequal forcing can lead to induced temperature gradients and therefore potentially drastic changes in circulation patterns that lead to climatic changes over various regions, including South Asia.

Following the mid-1980s, there was an upward trend in observed aerosol optical depth (AOD) in South and East Asia (Acharya & Sreekesh, 2013; Krishna Moorthy et al., 2013), while a decreasing aerosol trend is seen over North America and Europe (Mehta et al., 2016). More recently, anthropogenic sulfur dioxide emissions have started declining drastically over East Asia following emission control measures taken in China (Koukouli et al., 2016). Sulfate aerosol produced from fossil fuel SO₂ emissions is the dominant anthropogenic aerosol type (Myhre, Samset, et al., 2013) and is the focus of this study. Sulfate scatters shortwave radiation directly or indirectly by changing the microphysical properties of clouds (Albrecht, 1989; Twomey, 1977), with the overall effect being to strongly cool the climate system (Haywood & Ramaswamy, 1998).

Remote influences of aerosols on South Asian rainfall have been investigated only in a few past studies. Shindell et al. (2012) perturbed aerosol forcings at different latitude bands and examined precipitation responses around the globe, with South Asian precipitation response found to be more sensitive to aerosol forcings originating in the northern midlatitudes compared to forcings that originated in the tropics. Chakraborty et al. (2013) showed that remote aerosols from East Asia can impact atmospheric stability and monsoon rainfall of South Asia through modulation of upper tropospheric Rossby waves and low-level moisture transport. Bollasina et al. (2014) suggested that the decreasing trend in precipitation from preindustrial to the present day was partly driven by remote aerosols through their influence on large-scale temperature change patterns and on circulation, though the attribution was not done explicitly with experiments separating remote and local influences. The asymmetric distribution of sulfate aerosols, which are more prominently present in the Northern Hemisphere (NH), modifies the interhemispheric temperature gradient and leads to a southward migration of the ITCZ, reducing precipitation in the NH (Polson et al., 2014). On the other hand, Guo et al. (2015) used model data from the Fifth Coupled Model Intercomparison Project (CMIP5) and suggested that the negative trend in late-twentieth-century South Asian rainfall has been caused by local aerosol indirect effects. More recently, Guo et al. (2016) found that remote sulfate aerosols contributed to 75% of precipitation changes in the region, though this was estimated using atmosphere-only simulations and not a coupled ocean-atmosphere system.

Breaking down the aerosol influences on the Asian monsoon by region of emission was pursued to some extent by Dong et al. (2016), though for the East (not South) Asian summer monsoon and in an atmosphere-only model rather than an atmosphere-ocean model. They investigated the transient short-term evolution of the response of the monsoon to instantaneous changes in emissions in Asia and Europe. The study found that on time scales of around 40–90 days, the response of the monsoon was the same for both Asian and European emissions. Asian aerosols cooled the Asian land mass directly and reduced precipitation due to land-sea thermal contrast (LSTC) reduction, while European emissions led to midtropospheric cooling that was advected over to Asia, cooling the region and resulting in a similar East Asian monsoon response. More recent work by Dong et al. (2017) demonstrated that the responses in a coupled ocean-atmosphere system can be very different, even on decadal time scales; therefore, atmosphere-only simulations are only suitable for assessing very rapid responses. A study by Cowan and Cai (2011) using a coarse-resolution atmosphere-ocean model found that non-Asian aerosols exacerbate and reinforce the effect of Asian aerosols on the Asian monsoon through broader and more intense cooling of land temperatures in Europe and Asia. Finally, a more recent study by Acosta Navarro et al. (2017) investigated the effects of future emissions scenarios where aerosols are strongly decreased through the mid-21st century. They found that their model exhibited a broad warming over the NH and a northward shift of the ITCZ, and enhanced Asian monsoon circulation leading to increased precipitation in Southeast and East Asian regions. The studies highlighted above provide the context upon which we will present and discuss our results.

We address the need for a systematic study in a fully coupled model configuration, which allows us to explore the mechanisms that drive the full South Asian climate responses to the most important present-day aerosol forcer, namely, sulfate, produced by sulfur dioxide (SO₂) emissions. Using the U.K. Met Office’s Hadley Centre Global Environment Model Version 3 (HadGEM3)–Global Atmosphere 4.0 (GA4) general circulation model, we
present the first systematic analysis of how aerosol-producing anthropogenic emissions originating from different key regions, namely, East Asia (EAS), the United States (USA), Europe (EUR), and the northern midlatitudes as a whole (NML), can impact South Asian climate.

In section 2, we discuss the methodology, model evaluation, and experiments. Section 3.1 presents an overview of the precipitation responses to the regional SO2 emissions removals. In sections 3.2–3.5, we discuss the findings and suggest mechanisms that may be linking the emission changes to the climate responses. Finally, section 4 provides the conclusions of this study.

2. Methods

2.1. Model Description

This study uses the HadGEM3-GA4, which is a state-of-the-art global climate model (Walters et al., 2014). The horizontal resolution is 1.875° × 1.25° (longitude × latitude) with 85 vertical hybrid height levels up to 85 km in altitude. The atmospheric component of the model is coupled to the Joint UK Land Environment Simulator (JULES) land surface model (Walters et al., 2014), the Nucleus for European Modeling of the Ocean (NEMO) ocean model (Madec, 2008), the Los Alamos sea ice model CICE (Hunke et al., 2010), and the Coupled Large-scale Aerosol Simulator for Studies In Climate (CLASSIC) aerosol scheme (Bellouin et al., 2011). This setup provides explicit online simulation of fully interactive atmosphere, aerosol, land surface, ocean, and sea ice, which is able to follow the end-to-end sequence of processes from emission changes to a radiative forcing and climate response.

The CLASSIC aerosol scheme (Bellouin et al., 2011) is a mass-based scheme, where only the mass of aerosol is prognostic and the size distribution within each mode is parameterized. It includes sulfate, black carbon, organic carbon, biomass burning aerosol, mineral dust, sea salt, and secondary organic aerosols from biogenic emissions. Nitrate aerosol was not included here. The model simulates both direct and indirect aerosol radiative effects, including cloud brightening and cloud lifetime effects in the large-scale cloud scheme. It is the scheme used for the HadGEM2-ES (Earth System) simulations submitted to CMIP5 and included in the Intergovernmental Panel on Climate Change Fifth Assessment Report (Myhre, Shindell, et al., 2013). In the current study, the emissions of anthropogenic aerosols and their precursors are representative of the year 2000, taken from the Atmospheric Chemistry and Climate Model Intercomparison Project emissions data set (Lamarque et al., 2010).

Sulfate precursors (SO2 and dimethyl sulfide) are advected as tracers (as is sulfate itself and other aerosol species) and undergo oxidation by prescribed climatological oxidant fields of the hydroxyl radical (OH), ozone (O3), and hydrogen peroxide (H2O2; Derwent et al., 2003). Well-mixed greenhouse gas mixing ratios in the radiation code are set to their year 2000 values from the CMIP5 historical data set, while for ozone a zonally uniform present-day climatology from the Stratospheric Processes and their Role in Climate (SPARC) data set (Cionni et al., 2011) is used.

2.2. Model Biases

HadGEM3-GA4, like other coupled global climate models (Sandeep & Ajayamohan, 2014), shows biases when simulating precipitation over South Asia for the summer monsoon period. Specifically, there is too little rainfall over the land region and too much rainfall over the equatorial Indian Ocean. In the coupled model configuration, this is driven by a cold sea surface temperature (SST) bias in the Arabian Sea, caused by excessive north-easterly winds during the winter and premonsoon seasons. Cold SSTs lead to a low bias in moisture transport into the region by the southwesterly winds that are typical of the South Asian monsoon. These issues, which are common in global climate models, have been discussed extensively in previous studies such as Levine and Turner (2012), Levine et al. (2013), Marathayil et al. (2013), and Sandeep and Ajayamohan (2014).

Figure 1 shows the 150-year June–July–August (JJA) mean precipitation climatology for year 2000 in the control simulation (see section 2.3) over the South Asian region. It also shows the 30-year (1980–2010) JJA mean precipitation climatology from the Global Precipitation Climatology Project (GPCP) satellite observational data set used for comparison. As compared to the GPCP climatology, the model shows excessive rainfall in certain areas, as shown by peaks in precipitation along the Himalayan Mountain range in India and the Arakan Mountains along the Burmese coast. The equatorial Indian Ocean also has excessive rainfall with a maximum just north of the equator. On the other hand,
there is too little precipitation in the central part of India as compared to the GPCP climatology due to the dry bias discussed above. However, from Figure 1 we can say that the large-scale spatial pattern of precipitation in the model is broadly comparable to the observations, with the bias being mainly in the relative magnitudes of precipitation over ocean versus land.

Figure S1, taken from Kasoar (2016), compares the AOD between the HadGEM3-GA4 model (top panel) and observations (bottom panel) from Aerosol Robotic Network (AERONET) ground stations across the globe (Holben et al., 2001). AOD measures the extent to which the aerosol interacts with radiation and therefore is an important diagnostic when it comes to quantifying aerosol effects on climate. The simulation used in Kasoar (2016) is the same as the 150-year mean control simulation used in this paper. Figure S1 suggests that the spatial pattern and magnitude of AOD in the model compare well with the AERONET observations. In the regions that will be perturbed in the experiments (gray boxes), that is, the United States, Europe, and East Asia, the model performs quite well. Kasoar (2016) showed that globally, the model bias is around +15% and for each of the regions mentioned above having biases of similar magnitude (i.e., roughly between 10% and 20%). An evaluation of aerosol representation in this model and other models compared to satellite observations can also be found in Pan et al. (2015). They suggest that the HadGEM2 model (an earlier version of HadGEM3, but with the same aerosol scheme) compares well with observations in terms of total AOD over the whole of South Asia but overestimates AOD in Central India. However, in their study this was due to a positive bias in nitrate aerosol, which is not included in our version of HadGEM.

Finally, the seasonal migration of tropical rainfall resulting from variations in interhemispheric heating due to varying insolation is represented well in this model (Kasoar, 2016), which provides some confidence that the effect of NH aerosols on the ITCZ will also be reasonable. Also, despite the biases in monsoonal precipitation, the HadGEM2 model (an earlier version of HadGEM3) does still represent the climatology of 850-hPa winds as well as the spatial domain of the monsoon rainfall reasonably well among other CMIP5 models (Sperber et al., 2013). Based on all the above, for the results presented here on precipitation responses to SO2 emissions removals, the model's large-scale aerosol and climate representation is found to be satisfactory for our purposes.
2.3. Experiments

We performed 200-year-long simulations with repeated conditions. Perturbation simulations allowed us to isolate the effect of removing a particular emission from a specific region. The experiments are as follows: (1) Setting anthropogenic emissions of SO2 (precursor gas of sulfate aerosol) over the entire northern midlatitudes to zero while keeping the emissions of other gases and aerosols to present-day levels (this will be referred to as NML); 2) The same as (1) but setting the emissions of SO2 over East Asia to zero (EAS); (3) the same as (1) but for the United States (USA); (4) The same as (1) but for Europe (EUR); and (5) a control simulation (CTL), where all emissions are set to present-day (2000) levels and are unperturbed. See Table 1 for region definitions and a summary of experiments.

In order to explore whether the responses in temperature and precipitation are significant, we use a six-member ensemble of control simulations, each with different initial conditions. After discarding the first 50 years as model spin-up, we calculate the 150-year mean values of each realization and then calculate the standard deviation of the means. In the results that are to follow, the stippling on model grid points on the maps indicates when the magnitude of the response is greater than 2 standard deviations estimated from the six control simulations for each grid point. We analyze here the response in the 150-year JJA mean, which broadly corresponds to the South Asian summer monsoon season. We note that the perturbation simulations all started from the same initial conditions. Also, perturbation simulations are compared to one of the control simulations, that is, the one that shared the exact same initial conditions as all the perturbation runs. Only the atmospheric initial conditions differ between the different control runs (by initializing the atmosphere from a different start dump, corresponding to a different date taken arbitrarily).

The results from atmosphere-only (fixed-SST) simulations performed for all experiments (CTL, USA, EUR, EAS, and NML) are compared to the equivalent coupled simulations described above in order to explore differences in the fast response (driven by rapid adjustments in the atmosphere given by the fixed-SST response) and the slow response (driven by long-term SST changes, taken to be the total coupled response minus the fixed-SST response; Andrews et al., 2010; Bala et al., 2010; Ganguly et al., 2012; Samset et al., 2016). The observation-based SSTs used in these experiments were identical to those used for the HadGEM2 simulations performed as part of the Atmospheric Chemistry and Climate Model Intercomparison Project (Lamarque et al., 2010). The atmosphere-only simulations were performed for 26 years, and a 25-year mean is calculated, with the first year discarded as spin-up.

3. Results and Discussion

3.1. Overview of Precipitation Responses

This section presents an overview of precipitation responses, which are then discussed more in terms of physical mechanisms and processes in subsequent sections. Figure 2 shows the South Asian precipitation response calculated as the difference between the perturbation experiments and the control simulation. The responses are all characterized by a dipole over the tropical Indian Ocean, with precipitation increased north of the equator and decreased south of it, and also a large-scale increase in precipitation in most parts of South Asia. These effects are strongest in the NML experiment, the strongest and most zonally uniform perturbation to aerosol precursor emissions. The other experiments follow this pattern but with a smaller magnitude; however, the responses are still substantial and statistically significant.
Considering the detailed characteristics over land, it is seen that all responses feature pronounced positive anomalies at the tip of the Indian peninsula, the western coasts of India and Myanmar, and along the Himalayan mountain range, suggesting that over land, orography determines where the strongest responses occur. This pattern is also similar to the monsoon precipitation in the control climatology, meaning that the same factors that lead to excessive rainfall in these areas in the control simulation probably affect the pattern of increasing precipitation similarly. While the EAS and NML cases show increases ubiquitously over the inland region of India as well, the USA and EUR cases show small negative or no responses, particularly over Central India. USA and EUR have similar amounts of emissions that are removed (see Table 1), while EAS has 25% more emissions than USA and EUR, and NML has three times as much emissions removed as USA and EUR, suggesting that the rainfall in India could be more sensitive to either the stronger or more proximate forcing induced by the removal of SO$_2$ in East Asia. The role of the location of the emissions, and therefore of the forcing, will be discussed in more detail later in this paper (i.e., sections 3.4 and 3.5).

Figure 3 shows the zonal mean precipitation across 50°E–100°E for the CTL case (left panel), which peaks at ~5°N (ITCZ) and ~26°N (Himalayan orographic precipitation region). The responses due to the different experiments (right panel) confirm the northward ITCZ shift for all experiments. All the experiments except EAS show shifts directly around the equator. The shift in EAS is located a bit further to the north and has a more uniform distribution. The zonal mean response in the NML experiment resembles almost exactly the zonal mean rainfall pattern of the CTL case, influenced by the Himalayan Mountains. The other experiments all have a common increase around 5°N reflecting the similar dipole pattern caused by the ITCZ shift mentioned above, with some hint of a Himalayan pattern also in EUR (in USA and EAS, even though there are increases around the Himalayas, there are also neighboring decreases that compensate for them).
The emissions from the NML experiment include the vast majority of the emissions from the other midlatitude experiments (USA, EUR, and EAS). Since in Figure 2 the responses are all spatially similar but weaker in comparison to NML, this suggests some linearity across the responses. Figure 4a shows the sum of the USA, EUR, and EAS precipitation responses. The result is similar, in its spatial pattern and magnitude, to the NML response shown in Figure 2. The scatter plot in Figure 4b confirms this similarity quantitatively, showing the responses in each grid point within the 10°S–40°N, 30°E–140°E region when summing USA, EUR, and EAS, versus the corresponding responses in the NML experiment. This gives a high correlation coefficient of 0.81 \((p < 0.01)\), suggesting that the effects of aerosols from different midlatitude regions on the monsoon are linearly additive over this region and possibly share a common underlying driving mechanism. The precipitation responses in the individual experiments also positively correlate with that from the NML experiment.

**Figure 3.** (left) The 150-year June–July–August zonal mean precipitation (mm/day) averaged longitudinally between 50°E and 100°E for the control simulation (CTL) and Global Precipitation Climatology Project (GPCP) measurements, and (right) its change when removing SO2 emissions from the United States (USA), Europe (EUR), East Asia (EAS), and the northern midlatitudes (NML). The dashed line indicates the ±2 standard deviation of zonal mean precipitation inferred from the 150-year means of six control simulations.

**Figure 4.** (a) The 150-year JJA mean precipitation (mm/day) response derived from the sum of the USA, EUR, and EAS responses as shown in Figure 2; (b) scatter plot of the responses in each grid point shown in Figure 4a (box contained within 10°S–40°N, 30°E–140°E) when summing USA, EUR, and EAS \((x\text{-axis})\) versus corresponding responses in the NML experiment \((y\text{-axis})\). This has a correlation coefficient of 0.81 and \(p\) value < 0.01. JJA = June–July–August; USA = the United States; EUR = Europe; EAS = East Asia; NML = northern midlatitudes.
Following a similar line of thought, it suggests that there is a preferred response of large-scale precipitation to aerosols from different regions (Dong et al., 2016; Kasoar, 2016; Kasoar et al., 2018).

3.2. Fast and Slow Responses

The atmosphere-only 25-year mean JJA precipitation response to each perturbation is presented in Figure S3. In general, there are some common features over the land areas of Asia, with almost all of these experiments showing decreased precipitation in Central India (except NML), increased precipitation over the Himalayan Mountain Range, and a broad area of increases around 30°N latitude. However, much of the precipitation response over the oceans shows a quite noisy pattern, except for a common decrease around the eastern equatorial Indian Ocean. These simulations take into account only the fast atmospheric and land surface adjustments, so much of the response is due only to direct diabatic heating of the atmosphere, changes in surface evaporation, cloud changes, and fast atmospheric circulation adjustments. With the fully coupled response (Figure 2), the noise is largely reduced, allowing the response to be more clearly evident. This is because of the larger number of years used in the coupled simulations, while the fact that SSTs respond to and interact with the changes in the atmosphere caused by the perturbation allows for the full and more spatially coherent response to be realized.

Figure S4 shows the difference between coupled and atmosphere-only simulations, equaling what is often called the “slow response.” The positive response over the Indian land region seen in the coupled simulation is also evident here. Other studies have shown that the role of fast and slow drivers of precipitation is species dependent; for black carbon, fast stabilization effects due to atmospheric absorption can be important even when averaging on long time scales, while for sulfate the slow response is more important (Samset et al., 2016), in qualitative agreement with our findings here. In our case, though, the poor signal to noise in the fixed-SST simulations means that the slow response, diagnosed as a residual, is also very noisy. As a result, it is hard to compare with the total coupled response to quantify the relative importance of fast/slow responses here.

3.3. Large-Scale Behaviour

The NML experiment, where SO2 emissions are removed from the entire northern midlatitudes, is somewhat analogous to experiments conducted by Haywood et al. (2016), who performed simulations with sulfate aerosol injection into the Southern Hemisphere (SH) stratosphere and found influences on monsoon precipitation. In their experiments, an imbalance in the interhemispheric albedo as measured by top-of-atmosphere (TOA) reflectance is induced by the injection of the sulfate and consequently changes the transport of heat and moisture between the two hemispheres. Here AOD and TOA effective radiative forcing, calculated from equivalent atmosphere-only simulations, are used as proxies for hemispheric reflectance and energy input. Heat and moisture transport arguments are then used to explain the basic mechanism behind the increases of monsoon precipitation across all the experiments.

For each removal of SO2 emissions there is a reduction in total AOD (Figure S5) and a consequent radiative heating of the climate system as seen in Figure 5. These radiative forcings are largely localized to the regions of emissions and to nearby downwind areas. They do not involve any radiative perturbation over South Asia itself, except slightly so in the NML experiment. This extra heat is then redistributed across the hemisphere by the large-scale atmospheric and oceanic circulation. Figure 6 shows that in all cases, despite the regionally confined nature of the aerosol perturbations, the SST response is global but with the NH responding much more strongly than the SH, due to the stronger forcing in the NH (Figure 5). The NML experiment shows the strongest and most zonally uniform response. The other cases match the spatial pattern of NML, except for some remote areas in the Southern Ocean. The interhemispheric SST difference (IHSSTD) response is shown in Figure 7. The IHSSTD is calculated as the NH area-weighted mean minus the SH area-weighted mean of SST and shows the largest response in the NML experiment, as expected. In our model’s control simulation, the annual mean IHSSTD is 2.5 K. This is 0.7 K lower than the 3.2 K calculated based on observed temperatures for the period 1981–2010 from the Centennial in-situ Observation-Based Estimates (COBE) data set (Hirahara et al., 2014).

The climate system adjusts to this heating imbalance between the hemispheres by transporting the extra heat from the NH to the SH. We calculate the annual mean zonal mean cross-equatorial heat transport (CEHT) as an implied northward meridional heat transport as derived from the net TOA radiative fluxes,
Figure 5. The 25-year annual mean top-of-atmosphere net down effective radiative forcing (W/m²) when removing SO₂ emissions from the United States (USA), Europe (EUR), East Asia (EAS), and the northern midlatitudes (NML).

Figure 6. The 150-year JJA mean sea surface temperature response (ΔSST; in K) when removing SO₂ emissions from the United States (USA), Europe (EUR), East Asia (EAS), and the northern midlatitudes (NML).
The calculation of the heat transport at each latitude, adapted from Yang et al. (2015), is

$$\text{HT}(\varphi) = \int_{90^\circ S}^{90^\circ N} F_{\text{TOA}}(\varphi) \, d\varphi$$

where $F_{\text{TOA}}$ is the net downward TOA radiative fluxes integrated over longitude, $d\varphi$, and latitude. This is integrated from the first latitude at $90^\circ S$ through all latitudes to $90^\circ N$, and then the heat transport at the latitude $0^\circ N$ is selected to estimate the CEHT. The resulting CEHT changes are shown in Figure 7. It can be seen that all values are negative (indicating southward transport) and linearly scale with the amount of SO$_2$ emissions removed from each region (Table 1). The NML (USA) experiment has the largest (smallest) emissions removal and southward energy transport change.

Figure 8 shows the CEHT decomposed into its atmospheric and oceanic components, where the ocean heat transport is diagnosed directly in the model and the atmospheric component is inferred as the difference between the total and oceanic heat fluxes. The ocean heat transport response is greater in all cases, highlighting the important role played by the ocean in transferring heat and shaping the climate response on the multidecadal time scales examined here.

Atmospheric moisture transport between the hemispheres is driven by the Hadley circulation, which brings moisture at low levels from the winter hemisphere to the summer hemisphere (Heaviside & Czaja, 2013). At the equator, this moisture (and thus latent heat) transport opposes the CEHT (Haywood et al., 2016, and references therein), which occurs in the upper branch of the Hadley cell in the summer months (Heaviside & Czaja, 2013). Consistently with this line of thought, Figure 7 shows that for all experiments the response of cross-equatorial moisture transport is positive (northward), with the NML case responding more strongly than EAS, USA, and EUR. It is this anomalous transport of moisture that fuels the increases in rainfall in the northern tropics, manifests itself as a northward displacement of the ITCZ and thus strengthens the South Asian monsoon precipitation in every experiment, similar to the mechanism demonstrated by Haywood et al. (2016) for an aerosol perturbation in a very different context (stratospheric injection of sulfate in the SH).

In Table 2 we show the sensitivity of the South Asian summer precipitation to the annual mean IHSSTD changes, as measured by the ratio of the two quantities. Here we call this quantity the “Indian hydrological sensitivity” (IHS) since the region defined (10°N–30°N, 70°E–90°E) for the precipitation response captures most of India. The IHS is greatest in the EAS case, suggesting that the removal of SO$_2$ in this region is the most effective in driving a precipitation change in India through a unit change in IHSSTD. Table 2 also shows the precipitation response per unit emission (the regional precipitation potential [RPP]), and the precipitation response per unit global TOA effective radiative forcing (regional precipitation sensitivity [RPS]). These calculations demonstrate that the EAS experiment is generally the most effective in driving the precipitation response, whichever measure we use. This is particularly striking when considering the RPS, which is more than 4 times higher for EAS compared to NML. For the RPP, the EAS value is approximately 2 times higher compared to NML. The smaller difference between EAS and other experiments for RPP compared to RPS is a consequence of the fact that the radiative forcing efficiency (forcing per unit emission) of East Asian aerosols is lower compared to aerosols emitted in other midlatitude regions in the

### Table 2

| Experiment | Cross-equatorial heat transport (PW) |
|------------|-------------------------------------|
| USA        | -0.05                               |
| EUR        | -0.10                               |
| EAS        | -0.15                               |
| NML        | -0.20                               |

### Figure 7

Responses of various useful physical diagnostics in the different experiments: The first and second columns are the annual mean interhemispheric aerosol optical depth (AOD at 530 nm) difference change and interhemispheric sea surface temperature difference (IHSSTD; in K) response, respectively. These are calculated for each experiment by finding the area-weighted mean AOD or SST in Northern Hemisphere grid points minus Southern Hemisphere grid points. The third column is the annual mean zonal mean cross-equatorial heat transport (CEHT; in PW) response, and the fourth column is the annual mean cross-equatorial moisture transport (CEMNT; in g/kg m/s) response for each experiment, where northward is positive. The fifth column is the South Asian area mean (10°–30°N, 70°–90°E), June–July–August mean precipitation (Precip; in mm/day) response for each experiment, including an error bar calculated as 2 standard deviations inferred from six control simulations. All values are averaged over 150 years. The legend includes the annual mean amount of SO$_2$ emissions (in kg/s) removed from each region (experiment).

### Figure 8

Annual mean zonal mean cross-equatorial heat transport (CEHT; in PW) change for each experiment, USA, EUR, EAS, and NML, where northward is positive. For each experiment the total (Total; blue) CEHT is the same as in Figure 7, the oceanic component (Ocean; green) of the CEHT is derived from a model diagnostic and calculated directly by the model, and the atmospheric heat transport (Atmos; red) is derived by finding the difference between the total and oceanic components. USA = the United States; EUR = Europe; EAS = East Asia; NML = northern midlatitudes.
The IHS (70°E–90°E, 10°N–30°N) Calculated as the Ratio of the JJA Mean Precipitation Response Over India to the Annual Mean Global IHSSTD Change, the RPP Calculated as the Precipitation Response per Unit Emission, and the RPS Calculated as the Precipitation Response per Unit TOA Effective Radiative Forcing

| Experiment | IHS (mm·day$^{-1}$/K) | RPP (mm·day$^{-1}$/Tg·s$^{-1}$) | RPS (mm·day$^{-1}$/W·m$^{-2}$) |
|------------|------------------------|-------------------------------|-------------------------------|
| USA (458)  | 0.33                   | 0.13                          | 0.28                          |
| EUR (482)  | 1.01                   | 0.30                          | 0.58                          |
| EAS (663)  | 2.46                   | 0.70                          | 3.32                          |
| NML        | 1.10                   | 0.32                          | 0.75                          |

Note. The leftmost column also includes the annual mean amount of SO$_2$ emissions (in kg/s) removed from each region (experiment). IHS = Indian hydrological sensitivity; JJA = June–July–August; IHSSTD = interhemispheric sea surface temperature difference; RPP = regional precipitation potential; RPP = regional precipitation sensitivity; TOA = top of atmosphere; USA = the United States; EUR = Europe; EAS = East Asia; NML = northern midlatitudes.

At the most fundamental level, the LSTC between the Asian continent and the Indian Ocean drives the South Asian monsoon circulation (Li & Yanai, 1996) that transports moisture from the Indian Ocean into the land areas of South Asia. Since the East Asian emissions removal has a direct impact on the temperatures of the Asian continent through a widespread local positive radiative forcing (see Figure 5), especially compared to the USA and EUR experiments, we can possibly expect EAS (and NML) to feature the strongest influence on the monsoon circulation. Figure 9 shows the surface temperature responses over South Asia for all the experiments. This demonstrates the much stronger land response compared to the ocean response, which is to be expected due to the lower heat capacity of land compared to the oceans. Additionally, moisture constraints have been shown to enhance warming over land compared with over ocean on large scales, as the land surface warms faster than the neighboring ocean to maintain consistent moist static energy increases (Byrne & O’Gorman, 2018; Joshi et al., 2008). As expected, Figure 9 shows that the NML experiment features the strongest response, while the USA, EUR, and EAS responses are lower in magnitude. From the figure it is also noteworthy that remote responses from EUR and USA are quite substantial over Asia, despite the large distances of the corresponding emission regions and forcings. This is in line with the findings of the recent study of Kasoar et al. (2018), which discusses the global patterns of temperature and precipitation response from the same simulations analyzed here. Still, the EAS response causes a somewhat larger Asian surface temperature response compared with the USA and EUR responses. This is particularly true over China itself, despite the negative temperature response over India, the latter likely a consequence of an increase in cloudiness. The largest change in cloud amount is in the NML experiment followed by EAS, USA, and EUR (Figure S6). Large cloud increases in the EAS experiment (due to the strengthening of the monsoon bringing more moisture into the Indian subcontinent), particularly toward the northern and western parts of South Asia, can explain the negative temperature response over India as seen in Figure 9. Similarly, the NML experiment has a slightly weaker positive temperature response over central and northern India (Figure 9), also matching closely with the positive cloud response in these areas (Figure S6). There are much weaker cloud responses in this region in the USA and EUR experiments (Figure S6), and therefore, the temperature feature in central and northern India is less evident for these experiments (Figure 9).

Crucially, for the EAS experiment, the SST response over the Indian Ocean is quite small in comparison to the USA and EUR experiments (Figure 6), meaning that the LSTC between Asia and the Indian Ocean may be greater in the EAS case. The weaker Indian Ocean response in EAS is likely due to the fact that the pollution from East Asia is primarily advected toward the east over the Pacific Ocean and therefore away from the Indian Ocean. Subsequently, we use the NML experiment as a reference and compare the LSTC response for each case (Figure 10). It can be seen that the EAS experiment features the highest LSTC change as a fraction of the change in NML in all seasons. Indeed, half of the NML LSTC change is shown to be driven by the EAS response (assuming that the USA, EUR, and EAS responses linearly sum to the NML responses), despite present day, especially due to a saturation of aerosol-cloud interactions in the case of EAS (Kasoar et al., 2018; Liu et al., 2018; Wilcox et al., 2015). Both the RPP and the RPS are found to decline with the distance of the emission perturbation from South Asia, with USA being weaker than EUR, which is weaker than EAS. In other words, the most important remote contributor to the precipitation response over South Asia is East Asia, together with USA and EUR summing to give a roughly similar response to NML, as discussed above. This suggests that the there is a region dependence in the way that precipitation responds to emissions. Large-scale interhemispheric changes in temperature, heat, and moisture transport are possibly not the only factors that control the precipitation response over South Asia. Changes in monsoon circulation will be examined in the next section, demonstrating why East Asian emissions are the most influential.

From Table 2 it can also be inferred that per unit emission, the monsoon precipitation responses appear to be roughly additive, that is, the average of the RPPs in USA, EUR, and EAS is close to the RPP for NML.

### 3.4. Changes in the LSTC

At the most fundamental level, the LSTC between the Asian continent and the Indian Ocean drives the South Asian monsoon circulation (Li & Yanai, 1996) that transports moisture from the Indian Ocean into the land areas of South Asia. Since the East Asian emissions removal has a direct impact on the temperatures of the Asian continent through a widespread local positive radiative forcing (see Figure 5), especially compared to the USA and EUR experiments, we can possibly expect EAS (and NML) to feature the strongest influence on the monsoon circulation. Figure 9 shows the surface temperature responses over South Asia for all the experiments. This demonstrates the much stronger land response compared to the ocean response, which is to be expected due to the lower heat capacity of land compared to the oceans. Additionally, moisture constraints have been shown to enhance warming over land compared with over ocean on large scales, as the land surface warms faster than the neighboring ocean to maintain consistent moist static energy increases (Byrne & O’Gorman, 2018; Joshi et al., 2008). As expected, Figure 9 shows that the NML experiment features the strongest response, while the USA, EUR, and EAS responses are lower in magnitude. From the figure it is also noteworthy that remote responses from EUR and USA are quite substantial over Asia, despite the large distances of the corresponding emission regions and forcings. This is in line with the findings of the recent study of Kasoar et al. (2018), which discusses the global patterns of temperature and precipitation response from the same simulations analyzed here. Still, the EAS response causes a somewhat larger Asian surface temperature response compared with the USA and EUR responses. This is particularly true over China itself, despite the negative temperature response over India, the latter likely a consequence of an increase in cloudiness. The largest change in cloud amount is in the NML experiment followed by EAS, USA, and EUR (Figure S6). Large cloud increases in the EAS experiment (due to the strengthening of the monsoon bringing more moisture into the Indian subcontinent), particularly toward the northern and western parts of South Asia, can explain the negative temperature response over India as seen in Figure 9. Similarly, the NML experiment has a slightly weaker positive temperature response over central and northern India (Figure 9), also matching closely with the positive cloud response in these areas (Figure S6). There are much weaker cloud responses in this region in the USA and EUR experiments (Figure S6), and therefore, the temperature feature in central and northern India is less evident for these experiments (Figure 9).

Crucially, for the EAS experiment, the SST response over the Indian Ocean is quite small in comparison to the USA and EUR experiments (Figure 6), meaning that the LSTC between Asia and the Indian Ocean may be greater in the EAS case. The weaker Indian Ocean response in EAS is likely due to the fact that the pollution from East Asia is primarily advected toward the east over the Pacific Ocean and therefore away from the Indian Ocean. Subsequently, we use the NML experiment as a reference and compare the LSTC response for each case (Figure 10). It can be seen that the EAS experiment features the highest LSTC change as a fraction of the change in NML in all seasons. Indeed, half of the NML LSTC change is shown to be driven by the EAS response (assuming that the USA, EUR, and EAS responses linearly sum to the NML responses), despite present day, especially due to a saturation of aerosol-cloud interactions in the case of EAS (Kasoar et al., 2018; Liu et al., 2018; Wilcox et al., 2015). Both the RPP and the RPS are found to decline with the distance of the emission perturbation from South Asia, with USA being weaker than EUR, which is weaker than EAS. In other words, the most important remote contributor to the precipitation response over South Asia is East Asia, together with USA and EUR summing to give a roughly similar response to NML, as discussed above. This suggests that the there is a region dependence in the way that precipitation responds to emissions. Large-scale interhemispheric changes in temperature, heat, and moisture transport are possibly not the only factors that control the precipitation response over South Asia. Changes in monsoon circulation will be examined in the next section, demonstrating why East Asian emissions are the most influential.

From Table 2 it can also be inferred that per unit emission, the monsoon precipitation responses appear to be roughly additive, that is, the average of the RPPs in USA, EUR, and EAS is close to the RPP for NML.
the negative temperature response over much of India itself, as evident from Figure 9. This further supports the idea that East Asian emissions have the greatest influence on South Asian precipitation due to their stronger impact on the LSTC over East and South Asia. In the following section, the resulting local circulation changes are explored.

3.5. Local Dynamical Responses

On the large scale, and especially over the equatorial Indian Ocean, all the perturbations result in structurally similar changes in precipitation (Figure 2). More regionally, there are still notable differences in the location and magnitude of those changes, particularly over central and northern India where the USA and EUR SO2 removals resulted in much smaller precipitation increases and even decreases (Figure 2). Additionally, the strongest IHS and RPP were found for EAS (Table 2). Crucially, the LSTC, a key driver of the monsoon circulation, responds most strongly in the EAS experiment, as discussed above. But how exactly does the circulation respond in these experiments, with possible implications for precipitation?

In the climatological mean (Figure S7), as expected, the pressure over the Asian continent, particularly central Asia, is lower compared to the surrounding oceans. These pressure differences drive southwesterly winds over the Arabian Sea and Bay of Bengal, which then penetrate across the
South Asian land area, a typical feature in this region and season. These southwesterly winds transport moist air from the ocean that then condenses over land to form precipitation. Thus, an increase in the difference in meridional pressure gradient would result in stronger inflow of moisture (Chakraborty & Agrawal, 2017).

Figure 11 shows that the widespread removal of SO2 in NML causes anomalously low pressure over most of the land areas of Asia and anomalously high pressure over the Indian Ocean, inducing an all-round enhancement of the summer monsoon circulation, as demonstrated by comparing with the control simulation shown in Figure S7. The EAS experiment has a similar type of circulation response compared to NML, though weaker. Circulation (and pressure) responses in EUR and USA are weaker still, and it is clear that EAS is the main contributor out of the midlatitude regions to the all-round strengthening seen in the NML experiment. In EAS, and even more so in NML, the climatological southwesterly winds strengthen especially over the Arabian Sea. This circulation response aligns well with the LSTC arguments made earlier. It also explains why the cloud changes in the EAS experiment are so dramatic compared to the USA and EUR experiments (Figure S6). Figure 11 demonstrates that in all cases, but very strongly so in the EAS and NML experiments, there is a common region of reduced sea level pressure over much of China and over west Asia. The anomalous decrease in sea level pressure over west Asia in EAS (as compared to EUR and USA), as well as in NML, drives stronger westerlies over the Arabian Sea, bringing more moisture to South Asia, increasing rainfall. Our investigations showed that the variability of monsoonal winds over the Arabian Sea that bring moisture into the Indian subcontinent in the control simulation is strongly correlated with pressure anomalies over the Asian continent and in particular over eastern/central China (not shown). We can argue that the EAS and NML circulation responses shown in Figure 11 are projecting on to this variability pattern preexisting in the unforced (control) climate. Figure 12 shows the total column moisture flux response and its divergence for each experiment, demonstrating that the strengthened circulation particularly in the EAS and NML experiments translates into extra moisture being carried into the South Asian land area, with a qualitatively similar spatial pattern to the precipitation response (Figure 2).

Ultimately, these results suggest that the location of the emissions is important for shaping the exact precipitation changes over South Asia, since rainfall is largely determined by the summer monsoon circulation.
which, in turn, depends on LSTCs in the broader region. This circulation operates upon the large-scale tropical circulation following the ITCZ position that is driven by the hemispheric contrasts in temperature. On top of these background conditions, the LSTC and heating that induces specific patterns of sea level pressure anomalies modulate the circulation, moisture fluxes, and the final precipitation response and lead to the emission region dependences discussed earlier (Table 2) when it comes to the relationship between precipitation response and emission amount.

4. Conclusions

We have used a coupled atmosphere-ocean-aerosol global climate model, HadGEM3-GA4, to explore the impact of different idealized regional anthropogenic aerosol precursor emission reductions on precipitation in South Asia, focusing on the JJA period, which is the main part of the summer monsoon. These simulations involved removing present-day SO2 emissions from East Asia (EAS experiment), the USA, Europe (EUR), and the northern midlatitudes as a whole (NML). It was found that broadly, the precipitation response over South Asia and the Indian Ocean is qualitatively similar regardless of where the emissions were removed. Each experiment led to a reduced AOD in some locations of the NH, imposed a relatively localized positive radiative forcing, and also led to a large-scale increase in the north-south interhemispheric SST gradient. Because of the induced heating imbalance between the two hemispheres, additional heat is transported southward across the equator in order to readjust the climate system toward an equilibrium state. As a consequence, additional moisture is transported northward across the equator, opposing the changes in heat transport, supplying more rainfall to the tropical belt. This manifests as the precipitation associated with the ITCZ intensifying and shifting toward the warmer (northern) hemisphere, with one of the consequences being the strengthening of the South Asian summer monsoon.

Each localized experiment reveals results that are shown to be physically consistent and comparable with the large-scale zonal mean response, typified by the more drastic and more zonally uniform NML experiment, in terms of changes in the interhemispheric contrasts in AOD and SSTs, as well as in the CEHT and cross-equatorial moisture transport. There appears to be approximate linear additivity in the responses, in the

Figure 12. The 150-year June–July–August mean changes in total column moisture flux (arrows) and its divergence (shading; $10^{-5}$ kg m$^{-2}$ s$^{-1}$) when removing SO2 emissions from the United States (USA), Europe (EUR), East Asia (EAS), and the northern midlatitudes (NML). The unit vector is 20 kg m$^{-1}$ s$^{-1}$.
sense that the more localized experiments of USA, EUR, and EAS sum up to give a similar response seen in the NML experiment, with the largest contributor found to be EAS. This is shown to be particularly stark when viewing the precipitation response over India normalized by the IHSSTD, the emissions change or the TOA effective radiative forcing caused by each emissions perturbation.

Variations in the strength and the detailed spatial pattern of precipitation response over South Asia in the different simulations are largely controlled by differences in the regional dynamical response. East Asian SO2 emissions were shown to have a greater influence on the monsoon circulation, due to their direct and strong influence on the LSTC between land over Asia and the Indian Ocean. Additionally, the circulation response in EAS is similar to that in NML because of similar heating-induced sea level pressure changes over China, which is suggested to strongly influence the monsoon winds over the Arabian Sea and the Bay of Bengal. The conclusion here is that among other remote emissions, East Asian emissions clearly have the largest influence on precipitation over South Asia, because of their location, which is in close proximity to the region of interest, and therefore, they are most effective at triggering a response that projects onto the existing pattern of sea level pressure and monsoon circulation variability. Emissions from the United States and Europe act to amplify the response to East Asian emissions through changing large-scale temperatures and interhemispheric heat and moisture transport, all summing up in a linear fashion to the response seen when removing emissions from the whole of the northern midlatitudes.

Overall, the key message is that there is a striking qualitative similarity in the responses of South Asian monsoon precipitation irrespective of the emission region, but the location of the emission also has an important role to play for shaping the detailed features and magnitude of the response.

Despite the comprehensive nature of these experiments, there is a need for other fully coupled models to perform similar multiregional perturbation experiments, in order to allow for model intercomparison and examination of the robustness of our findings. Signs of this approach are beginning to take shape with efforts such as the Precipitation Driver Response Modelling Inter-Comparison Project (Myhre et al., 2016) demonstrated in Liu et al. (2018). Furthermore, it is important to also examine the effects of local (South Asian) aerosol emissions on the monsoon in the same model to compare the local and remote aerosol impacts, which will be the focus of a future study. Despite the scope for further studies, our work clearly demonstrates that when examining the behavior of the South Asian monsoon system over long time scales, it is crucial to consider the influences of the evolution of air pollutants such as aerosols even in regions that are located very remotely to South Asia, and it is important to do so using a coupled ocean-atmosphere modeling framework. Simultaneously, our results highlight the need for international cooperation when designing emission control policies, as domestic emission changes are far from being the only player in terms of shaping a region’s climate. The results from the idealized single-species aerosol reduction experiments presented here will inform the interpretation of monsoon responses to realistic emission scenarios in future studies.

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