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LETTER

Effects of local and remote black carbon aerosols on summer monsoon precipitation over India

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Supplementary material for this article is available online

Abstract

In this study, we perform idealized climate model simulations to assess the relative impacts of an increase in local black carbon (BC) aerosols (located over the Indian region) and the remote BC aerosols (located outside the Indian region) on the summer monsoon precipitation over India. We decompose the precipitation changes into fast adjustments triggered by the introduction of the forcing agent and slow response that is associated with the global mean temperature change. We find that a 60-fold increase in the 'present-day' global distribution of BC aerosols leads to an increase in precipitation over India, which is mainly contributed by an increase in remote BC aerosols. When remote BC aerosols are increased, the fast adjustments contribute to an increase in precipitation in association with the warming of the northern hemisphere land and the related northward Intertropical Convergence Zone (ITCZ) shift. For an increase in local aerosols too, by enhancing the upper tropospheric temperature meridional gradient in the Indian region, the fast adjustments contribute to an increase in precipitation over India. The slow response contributions in both cases are related to the regional patterns of SST change and the resulting changes to meridional temperature gradient in the Indian region and zonal circulation changes. The net precipitation change over India is an increase (decrease) for an increase in remote (local) BC aerosols. As the interpretation of our results relies on ITCZ shift related to planetary energetics, differing land-ocean response and meridional temperature gradients in the Indian region, the results from our study are likely to be robust across climate models.

1. Introduction

Black carbon (BC) aerosols absorb solar radiation in contrast to sulfate aerosols which primarily scatters solar radiation. Absorption of solar radiation by BC aerosols (direct effect) would warm the climate, but it would also cause a reduction in downwelling solar radiation at the surface (dimming effect) leading to a reduction in evaporation and precipitation (Ramanathan *et al* 2005, Yoshimori and Broccoli 2008, Ming *et al* 2010, Modak and Bala 2019, Sand *et al* 2020). BC aerosols also affect the climate system by altering the clouds through local heating (semi-direct effect) or by acting as cloud condensation nuclei (indirect effect) and thereby altering the radiative properties of clouds and circulation.

Several past studies have shown that absorbing aerosols such as BC aerosols modulates the hydrological cycle over India (Sanap and Pandithurai 2015, Li *et al* 2016 and the references therein). The BC aerosol forcing drives the changes in the Indian monsoon precipitation through mechanisms such as local atmospheric warming (Lau *et al* 2006, Lau and Kim 2006, Meehl *et al* 2008, Kovilakam and Mahajan 2016), reduction in downwelling radiation at the surface (Ramanathan *et al* 2005, Meehl *et al* 2008), change in meridional sea surface temperature

(SST) gradient (Ramanathan *et al* 2005, Chung and Ramanathan 2006, Meehl *et al* 2008, Ganguly *et al* 2012), and shifts in the location of Intertropical Convergence Zone (ITCZ, Wang 2004, Modak and Bala 2019).

Lau *et al* (2006) find that the absorbing aerosols along the slopes of the Tibetan plateau could heat the air in these elevated levels during the pre-monsoon months and strengthen the monsoon circulation. This in turn increases the precipitation over northern India (the so called 'elevated heat pump' mechanism - Lau *et al* 2006, Lau and Kim 2006). However, Lau *et al* (2006) also find that precipitation could decline over central India because of the BC induced surface cooling. Other studies such as Meehl *et al* (2008) and Kovilakam and Mahajan (2016) also find that the increase in the meridional tropospheric temperature gradient due to absorption of solar radiation by BC aerosols could enhance the monsoon circulation and precipitation over India.

An increase in precipitation in the India monsoon can be also associated with a BC-induced northward shift in the tropical precipitation maximum (ITCZ). For instance, Wang (2004) simulate, because of BC aerosols, an enhancement of the annual mean precipitation over India in association with a northward shift in ITCZ. In another study, Wang *et al* (2009) find that the absorbing aerosols alters the meridional gradient of the moist static energy in the sub-cloud layer and causes a northward shift in precipitation, which enhances the Indian monsoon. A recent study by Modak and Bala (2019) on the efficacy of BC aerosols finds that a global BC forcing causes a northward shift of the ITCZ. Because of this shift, they find that the annual mean precipitation increases in the northern hemisphere tropics. The ITCZ shift also has relevance to the recent trends in Indian summer monsoon rainfall: Hari *et al* (2020) find an increasing trend in Indian monsoon precipitation after the year 2002, and they attribute this trend to the northward shift in the location of ITCZ.

Several modeling studies show that SST changes due to BC aerosol forcing could also be as significant as the other factors discussed above (e.g., Ramanathan *et al* 2005, Chung and Ramanathan 2006, Meehl *et al* 2008, Ganguly *et al* 2012). Ramanathan *et al* (2005) simulate a reduction in precipitation over the Indian region in association with local atmospheric brown clouds which is mainly composed of absorbing aerosols such as BC, organic carbon, and dust. They find that the reduction in precipitation is associated with a reduction in surface solar radiation and surface temperature, stabilization of the troposphere, and a weakening of meridional SST gradient and monsoon circulation in the Indian Ocean region. Chung and Ramanathan (2006) show that a weakening in the SST gradient during summer weakens the monsoon circulation, leading to a decrease in monsoon rainfall over India. Other studies such as Meehl *et al* (2008) and Ganguly *et al* (2012) also find that the weakening meridional SST gradients due to BC aerosol forcing and associated changes could reduce the Indian summer monsoon precipitation.

Most of these past studies have investigated the precipitation response over the Indian region for an increase in the global distribution of aerosols. However, several recent studies have also assessed the role of local versus remote BC aerosols. For instance, Ganguly *et al* (2012), Bollasina *et al* (2014), Chakraborty *et al* (2014), Guo *et al* (2016), and Singh *et al* (2019) have investigated the impacts of local versus remote aerosols on the Indian monsoon, and Liu *et al* (2018) and Persad and Caldeira (2018) have explored the influence of regional aerosol emissions on the global temperature and precipitation. Ganguly *et al* (2012) find that local aerosols predominantly modulate the precipitation during the early monsoon period, whereas both local and remote aerosols have almost equal contribution in the summer monsoon season. Bollasina *et al* (2014) find that local anthropogenic aerosols play a predominant role in altering the Indian summer monsoon precipitation compared to the remote aerosols whereas Guo *et al* (2016) find that the remote BC aerosols have a dominant contribution in changing the precipitation over India. Chakraborty *et al* (2014) show that the impact of warming by remote aerosols can be as important as warming due to local aerosols for the Indian summer monsoon. Soni *et al* (2018) show that, during the pre-monsoon season, local BC aerosols enhance the precipitation over India, but during the summer monsoon season a differential warming due to warming of Bay of Bengal and cooling of Indian land region enhances (reduces) precipitation over north (south) India.

Further, the influence of remote aerosol forcing from different regions could be linearly additive for the Indian monsoon rainfall. For instance, Shawki *et al* (2018) show that the impact of such regional aerosol changes in South Asian summer monsoon can be linearly additive, as the sum of the responses to the regional forcings is similar to the response to the forcing from the whole northern midlatitudes. Moreover, Sherman *et al* (2021), using PDRMIP multi-model dataset, find that the Indian monsoon response to BC aerosols from India and China has large uncertainty partly due to the model differences in simulating changes in cloud vertical profiles.

Although previous studies have investigated the effects of BC aerosols and local versus remote BC aerosols on precipitation over India, the relative influence and the mechanisms that cause changes in precipitation over India remains unclear. In this study, we revisit the issue of the relative impacts of local versus remote BC aerosols on precipitation over India. To provide a systematic explanation of the mechanisms associated with the changes in precipitation due to local or remote BC aerosols, we decompose the total response of the climate system into fast adjustments and slow response (Andrews *et al* 2009, Bala *et al* 2010, Dong *et al* 2009). The fast adjustment refers to the adjustments of the atmosphere and land surface that are associated with the effective radiative

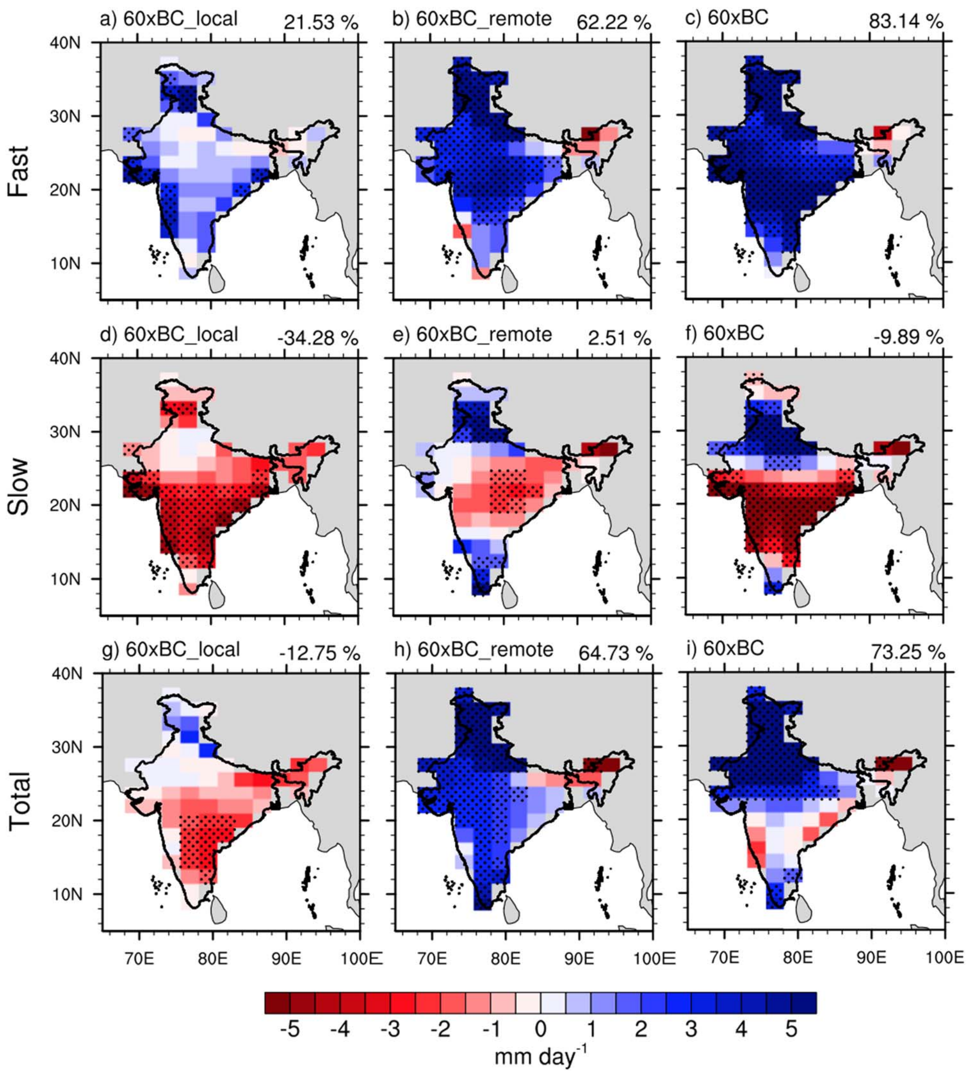

Figure 1. The contribution to June to September (JJAS) mean precipitation (mm day^{-1}) over India by fast adjustments (top panels), slow response (middle panels) and the total change (bottom panels) in the 60xBC_local (left panels), 60xBC_remote (center panels) and 60xBC (right panels) experiments relative to the 1xBC simulation. The procedure to estimate the fast adjustments, slow response, and total response are discussed in the text (section 3). The mean changes (in percentage) over India are shown in the top right corner of each panel. The stippling in the panels indicates the regions where the changes are larger than two standard deviations (confidence level of about 95%) estimated from 20 JJAS means of the 1xBC prescribed-SST simulation for the fast adjustments, and 50 JJAS means of the 1xBC SOM experiment for the slow response and total response.

forcing before any change in global-mean surface temperature (Bala *et al* 2010). The slow response or slow feedback refers to changes that are related to and that scale with the changes in global mean surface temperature.

The 'fast versus slow' response framework has been recently adopted by Wang *et al* (2017) to understand the impact of sulfate and BC aerosol forcing on East-Asian monsoon, and clear distinction between the mechanisms contributing to change in precipitation in the fast adjustment and slow response phases has been found for the East Asian monsoon. For the Indian summer monsoon too, the mechanisms associated with fast adjustments such as aerosol induced warming and slow feedbacks associated with SST changes are likely to differ for local and remote aerosols. To our knowledge, there is a lack of clear understanding of such mechanisms for the Indian monsoon and this paper attempts to fill this void.

In this study, we focus on changes in precipitation only over the country, India (figure 1) as the fast adjustment and slow response over India could be different from these responses over the surrounding ocean areas as demonstrated in section 4. Unlike past studies such as Guo *et al* (2016) which uses observed or slightly enhanced magnitude for BC forcing, we perform the BC forcing simulations with larger forcing magnitude (as in Kovilakam and Mahajan 2016) so that the climate response signal is well above the climate noise which enables unambiguous attribution of the climate response to BC forcing.

2. Model

We use the Community Atmosphere Model, CAM5 (Neale *et al* 2012) coupled to the Community Land Model CLM4 developed by the National Centre for Atmospheric Research (NCAR). We perform our simulations using two configurations: (1) prescribed-sea-surface-temperature (prescribed-SST) configuration to estimate the fast adjustments and (2) slab ocean model (SOM) configuration to compute the total climate response. The SOM is a simplification of the full ocean model and it is useful for studying equilibrium climate change on decadal time scales which is the timescale for the slab ocean to reach equilibrium. Our simulations use a configuration with a horizontal resolution of $1.9^\circ \times 2.5^\circ$ (latitude $\times$ longitude) and 30 vertical levels for the atmosphere—model top is at ~3.5 hPa (Neale *et al* 2012).

In the default configuration, CAM5 is coupled to the Modal Aerosol Model (Liu *et al* 2012) where BC aerosols are emitted. However, in this study, CAM5 is coupled to the Bulk Aerosol Model (BAM, Emmons *et al* 2010, Lamarque *et al* 2012, Tie *et al* 2005) where aerosols are prescribed. Adopting CAM5-BAM reduces the computational time needed for the model simulations. BAM simulates only the direct (radiative effect of scattering and absorption by the aerosols) and the semi-direct effects (changes in climate due to the local heating from absorbing aerosols such as BC) of tropospheric aerosols. The indirect aerosol effect, in which aerosol particles act as cloud condensation nuclei and thereby alter the radiative properties of clouds, is not considered. A detailed discussion of BAM is provided in Neale *et al* (2012) and Modak and Bala (2019).

3. Experiments

We perform four idealized simulations (table S1): (1) a '1xBC' or 'control' simulation with prescribed BC aerosol distribution corresponding to the year 2000 (referred to as present-day), (2) a '60xBC' simulation, which is same as 1xBC, but the prescribed BC mixing ratio is 60 times the present-day climatology - spatial distribution is same as the present-day climatology, and only the magnitude of aerosol mixing ratio is increased (figure S1a (available online at stacks.iop.org/ERC/3/081003/mmedia)), (3) a '60xBC_local' simulation, which is same as 60xBC, but BC mixing ratio is increased only over the Indian region (5°–40°N, 65°–95°E, figure S1b) and (4) a '60xBC_remote' simulation, which is same as 60xBC, but BC mixing ratio is increased throughout the globe except the Indian region (figure S1c). As discussed earlier, all these four simulations are performed in two different configurations—prescribed-SST and SOM. The SOM simulations are performed for 100 years and the last 50 years are used for the estimation of total response to the forcings, and the last 20 years of the 40-year prescribed-SST simulations are used for the estimation of fast adjustments (Table S1). The slow response is estimated as the difference between the total response and fast adjustments as discussed in Bala *et al* (2010).

Our choice of increasing the mixing ratio of BC aerosols by 60-fold in the 60xBC experiment is determined by the constraint that we simulate the same equilibrium global mean surface warming as for a doubling of atmospheric carbon-dioxide in this model (Modak and Bala 2019). In all the experiments, we have applied the forcings as step function change at the start of the simulations. The distribution of all greenhouse gases and all other aerosols are prescribed at the pre-industrial level in all the simulations.

4. Results

In this study, unless specified, the changes shown for 60xBC, 60xBC_local and 60xBC_remote cases are relative to the 1xBC case. The difference between the 60xBC and 1xBC cases represents the response to an increase in 'global' BC aerosols, the difference between the 60xBC_local and 1xBC cases represents the effect of an increase in 'local' BC aerosols, and the difference between the 60xBC_remote and 1xBC cases represents the effect of an increase in 'remote' BC aerosols.

4.1. Energy budget changes and ITCZ shift

First, we briefly discuss the hemispheric energy budget changes and the associated changes in cross-equatorial heat transport and the global mean ITCZ shifts in the 60xBC, 60xBC_remote and 60xBC_local experiments. This brief discussion would facilitate the understanding of the regional precipitation response over India to local and remote BC aerosols which is discussed in section 4.3. The full details on the estimation of cross-equatorial heat transport and the global mean ITCZ shift are discussed in Modak and Bala (2019). It is shown in Modak and Bala (2019) that the BC aerosol forcing leads to relatively a larger warming of the northern hemisphere compared to the southern hemisphere, and the resulting change in interhemispheric temperature difference leads to a northward shift in the location of ITCZ and an enhancement of precipitation in northern hemisphere tropics.

In our experiments, as in Modak and Bala (2019), the spatial distribution of BC aerosols is asymmetric about the equator with more BC aerosols in the northern hemisphere than the southern hemisphere (figure S1). The asymmetric distribution alters hemispheric energy budgets which causes shift in ITCZ (Donohoe *et al* 2013, Byrne *et al* 2018, and the references therein). The changes in planetary energy budget and the associated changes in the location of ITCZ in our experiments are shown in table S2. As the BC aerosol distribution in the 60xBC_remote experiment is almost similar to the 60xBC experiment, the changes in the 60xBC_remote experiment are similar to the changes in the 60xBC experiment discussed in Modak and Bala (2019). In the 60xBC_remote case, a 60-fold increase in BC aerosols causes an increase in interhemispheric aerosol optical depth (AOD) difference by 0.11 (Table S2). In contrast, the change in hemispheric difference in AOD is much smaller in the 60xBC_local experiment (0.02). The increase in BC aerosols causes an interhemispheric radiative forcing difference (of ~9 W m^{-2}) and an increase in the interhemispheric temperature difference of ~4 K in the remote and global BC experiments (Table S2). The warming of northern hemisphere and the associated change in meridional temperature differences necessitate a southward atmospheric heat transport anomaly (AHT). The southward AHT at the equator (AHT_{eq}) is ~1 PW in the remote and global cases. The southern hemisphere Hadley cell would shift into northern hemisphere along with a northward shift in ITCZ in association with this southward cross-equatorial heat transport (Donohoe *et al* 2013). Correspondingly, a northward shift in location of the ITCZ by ~7 degrees is also simulated in the remote and global cases. In the case of local BC aerosols, BC-induced warming is much less, and hence the magnitude of the change in interhemispheric temperature difference, AHT_{eq} and ITCZ shift are smaller relative to the 1xBC case (Table S2).

4.2. Precipitation response to an increase in 'global' BC aerosols

For a global annual mean surface warming of ~4.1° K, a decrease in the global annual mean precipitation by ~8% (figure S2i) in the 60xBC case is simulated by Modak and Bala (2019), which is qualitatively in agreement with several past studies (e.g., Andrews *et al* 2010, Mahajan *et al* 2013, Samset *et al* 2016). The net decrease in precipitation in the 60xBC case is contributed by a reduction in precipitation by ~18% during the fast adjustments and an increase by ~10% in the slow response phase (figure S2c, f). The reduced precipitation during the fast adjustments is mainly due to (1) a reduction in solar insolation at the surface which leads to a decrease in evaporation and hence precipitation (Yoshimori and Broccoli 2008, Ming *et al* 2010, Ban-Weiss *et al* 2012), and (2) an increase in the atmospheric stability due to SW absorption in the upper atmosphere (Ming *et al* 2010, Frieler *et al* 2011, Modak and Bala 2019, Sand *et al* 2020).

Although the global annual mean precipitation decreases, the precipitation over India increases (figure S2i) with the increase in global BC aerosols, which is consistent with several past studies (e.g., Mahajan *et al* 2013, Kovilakam and Mahajan 2016, Samset *et al* 2016, Modak and Bala 2019). In the next section, we discuss the relative contributions from the local and remote BC aerosols to this increase in precipitation over India and the associated mechanisms. As the summer monsoon (June to September - JJAS) precipitation contributes about 80% to the annual precipitation over India (Parthasarathy *et al* 1994), we focus on the changes during this season in the next section.

4.3. Precipitation response to local versus remote BC aerosols over India

The JJAS mean fast and slow components and total precipitation response to global, local and remote BC aerosols over India are shown in figures 1 and 2. The precipitation response to local and remote BC aerosol forcings does not add linearly to produce the precipitation response to global BC forcing over India in our simulations. The total precipitation response to global BC aerosols (the 60xBC case) differs by approximately 20% from the sum of the response in the 60xBC_local and 60xBC_remote cases (figures 1 and 2). This indicates that the interaction between local and remote effects are not negligible over the small region, India. However, the sign of the changes in the 60xBC case does not differ from the sum of the response over India for the fast adjustments, and slow and total response (figure 2). Further, similar to the results from Guo *et al* (2016), we find that the precipitation response to local and remote BC aerosol forcings add almost linearly to produce the precipitation response to global BC forcing over the larger Indian region (0°–40°N, 65°E–95°E, figure S3).

An increase in global BC aerosols by 60 times leads to an increase in JJAS precipitation over India by ~73% (figure 1(i)), which is primarily contributed by the fast adjustments (~83%, figure 1(c)). The increase in precipitation is mainly contributed by remote BC aerosols (~65%, figure 1(h)) which overwhelms a reduction caused by the local BC aerosols (~13%, figure 1(g)). The increase in precipitation over India due to remote aerosols is contributed predominantly by the fast adjustments (~62%, figure 1(b)). Precipitation over India increases in the 60xBC_local experiment during the fast adjustments (~22%, figure 1(a)), but a reduction of similar but slightly larger magnitude (~34%, figure 1(d)) is simulated in the slow response phase. The result is a net decline in the JJAS mean precipitation due to the local BC aerosols (~13%, figure 1(g)).

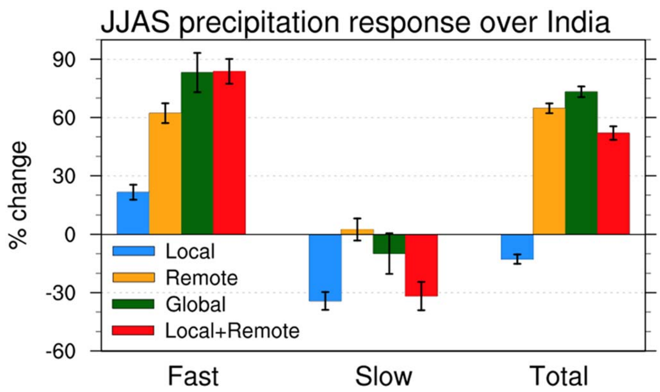

Figure 2. Percentage changes in June to September (JJAS) mean precipitation over India from fast adjustments, slow response, and total response due to a 60-fold increase in local, remote and global BC aerosols. The procedure to estimate the fast adjustments, slow response and total response are discussed in the text (section 3). The uncertainties in changes are represented by 2 standard errors computed from 20 JJAS means from the prescribed-SST simulations for the fast adjustments and 50 JJAS means from the SOM simulations for the slow and total response.

4.3.1. Fast adjustments for an increase in local BC aerosols

During the fast adjustments in the 60xBC_local simulation, the land surface cools over India (figure S4). The tropospheric stability increases due to larger warming of the upper troposphere (figure S5a). The surface cooling is a result of the reduction in solar insolation at the surface due to the absorption of solar radiation in the upper atmosphere by the increased BC aerosols (dimming effect, Ramanathan *et al* 2005, Yoshimori and Broccoli 2008, Ming *et al* 2010, Frieler *et al* 2011, Ban-Weiss *et al* 2012, Soni *et al* 2018, Modak and Bala 2019). The tropospheric warming is larger over the Indian land region than over the ocean (figure S5a) as the BC aerosol concentration is larger over land (figure S6). Tropospheric warming and surface cooling lead to an increase in tropospheric stability over the land and ocean areas (figure S5a). Although the atmosphere is stabilized due to the warming by local BC aerosols, precipitation increases in the fast adjustment phase over the Indian region (figure S3a). This increased precipitation is associated with the upward motion over the Indian region (figure 3 and S5b). The upward motion over the Indian region during the fast adjustments is associated with an enhanced upper tropospheric meridional temperature gradient between northern India and the areas to the south (figure 3(b)). The increase in upper tropospheric temperature gradient is related to larger absorption of solar radiation by BC aerosols over India compared to the ocean areas to the south (figure 3(a)). This is in agreement with previous studies which show that the BC-induced warming over the Indo-Gangetic Plains and Tibetan Plateau generates a north-south tropospheric temperature gradient which enhances upward motion over the Indian region (the 'elevated heat pump' effect, e.g., Lau *et al* 2006, Lau and Kim 2006, Meehl *et al* 2008, Kovilakam and Mahajan 2016). This heat pump leads to the strengthening of the monsoon Hadley cell which overwhelms the increase in vertical stability and leads to an increase in upward motion, cloudiness and precipitation over the Indian region (figure 3(c) and S7a, b). As the stabilization of troposphere is less over the oceanic region than the Indian land region (figure S5a), a larger precipitation increase is simulated over the oceanic region (figure S3a).

4.3.2. Slow response for an increase in local BC aerosols

In the slow response phase of the 60xBC_local simulation, the local BC aerosols cause a reduction in precipitation over India in our simulations (figures 1(d) and 2). This is likely associated with a cooling of the North Indian Ocean in the slow response phase (figure 4(a)) which is the expected ocean response when it is allowed to respond to reduced solar radiation reaching the surface. Although the North Indian Ocean cools during this phase, an area of relatively warmer SST is simulated over the Western Pacific (figure 4(a)). The horizontal temperature gradient between the North Indian and Western Pacific region is associated with a 'Walker-cell circulation' with a low-level flow from the Indian Ocean to Western Pacific (figure S8a). The direction of flow is reversed in the upper troposphere completing an overturning circulation in the zonal direction connecting the North Indian Ocean and Western Pacific (figure 4(b) and S8b). This circulation is associated with subsidence over the North Indian Ocean and an upward motion over the Western Pacific and decrease (increase) in cloudiness and precipitation over the North Indian Ocean (Western Pacific) (figure 4(b) and S7c, d). The reduction in precipitation over India could be also related to the weaker north-south gradient of SST in the Indian Ocean, as the North Indian Ocean cools more than the South Indian Ocean (figure 4(a)). This is consistent with several previous studies (e.g., Ramanathan *et al* 2005, Chung and Ramanathan 2006, Ganguly *et al* 2012) that have shown that a weaker meridional SST gradient can weaken the monsoon circulation and

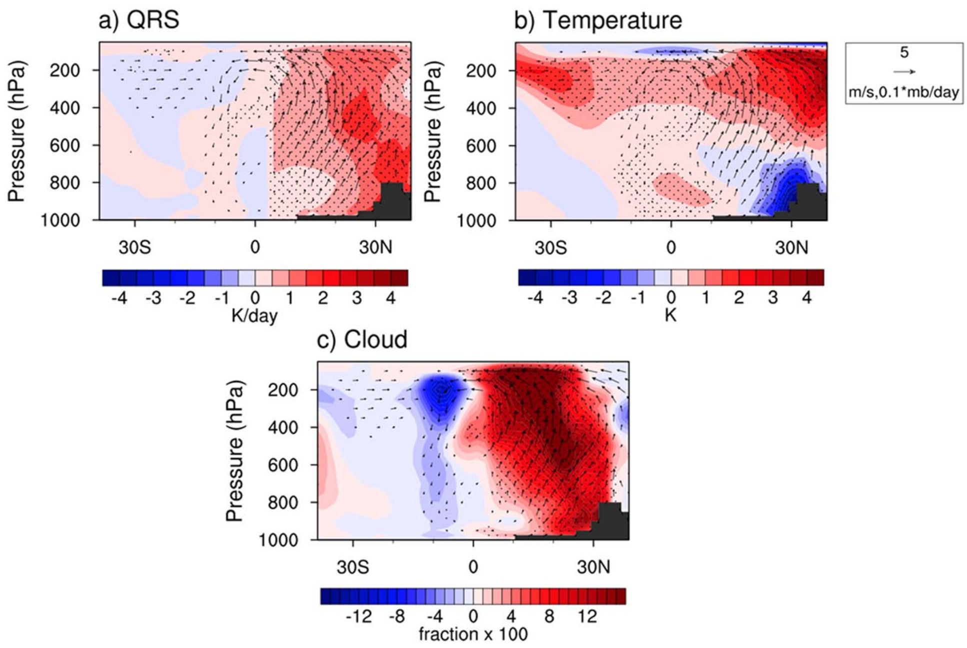

Figure 3. The changes in zonally averaged (65°E–95°E) June to September (JJAS) mean (a) shortwave heating (K day^{-1}), (b) temperature (K), and (c) cloud fraction over the Indian region (65°E to 95°E) for the 60xBC_local case relative to the 1xBC simulation during the fast adjustments as estimated from the prescribed-SST simulations. The vectors represent the changes in meridional circulation depicted by meridional wind (v, m s^{-1}) and vertical pressure velocity ($-\omega$, 0.1*mb day^{-1}). The stippling in the panels indicates the regions where the changes in shortwave heating (a), temperature (b) and cloud fraction (c) are larger than two standard deviations (confidence level of about 95%) estimated from 20 JJAS means of the 1xBC prescribed-SST experiment.

reduce the precipitation over India. In summary, the cooling in the ocean areas surrounding India leads to a reduction in precipitation over India during the slow response phase.

4.3.3. Fast adjustments for an increase in remote BC aerosols

During the fast adjustments in the 60xBC_remote simulation, the remote BC aerosols cause a large scale warming of the land regions in the northern hemisphere particularly over the Eurasian and North American continents, and the magnitude of this warming is larger in northern hemisphere summer (figure 5(a)). In association with the consequent change in interhemispheric temperature difference, a northward shift in ITCZ is implied (Donohoe *et al* 2013, Devaraju *et al* 2015, Nalam *et al* 2018). Hence, a northward shift in precipitation is simulated over the Indian and African monsoon regions relative to the 1xBC experiment (figure 5(b)).

4.3.4. Slow response for an increase in remote BC aerosols

In the slow response phase, Modak and Bala (2019) show that a global increase in BC aerosols (in the 60xBC simulation) leads to larger warming of the northern hemisphere than the southern hemisphere (by ~4 K), which causes a northward shift of ITCZ and an increase in annual precipitation in the northern hemisphere tropical regions. In the 60xBC_remote simulation, during JJAS, a meridional shift in precipitation is clearly seen over the Atlantic and Pacific Ocean basins but an increase in precipitation is simulated over the whole Indian Ocean basin (figure S9). Although tropical precipitation changes can be related to the shift in ITCZ caused by interhemispheric temperature differences, there could be large variability in the shifts along the zonal direction (Atwood *et al* 2020), as precipitation changes can be also influenced by local factors such as land-ocean thermal gradient for the Afro-Asian monsoon, and SST pattern in the tropical eastern Pacific and Atlantic in case of the North American monsoon (Cao *et al* 2020).

In the slow response phase, precipitation decreases over central India and increases over the North Indian Ocean. The associated JJAS 850 hPa circulation pattern shows a weakening of the monsoon low level circulation (figure 6(b)). The decrease in precipitation over central India can be associated with the changes in land-ocean temperature gradient in the 60xBC_remote experiment, where the North Indian Ocean warms more than the Indian subcontinent as the ocean is allowed to respond in the slow response phase (figure 6(a) and S10). Previous studies have also shown that a larger warming of the Indian Ocean relative to the Indian subcontinent can lead to a weakening of the Indian summer monsoon (Jin and Wang 2017, Roxy 2017).

Following Jin and Wang (2017), the land-ocean temperature gradient is estimated as the difference in area-averaged surface temperature between the Indian Peninsula (10°N–30°N, 70°E–90°E) and the tropical Indian

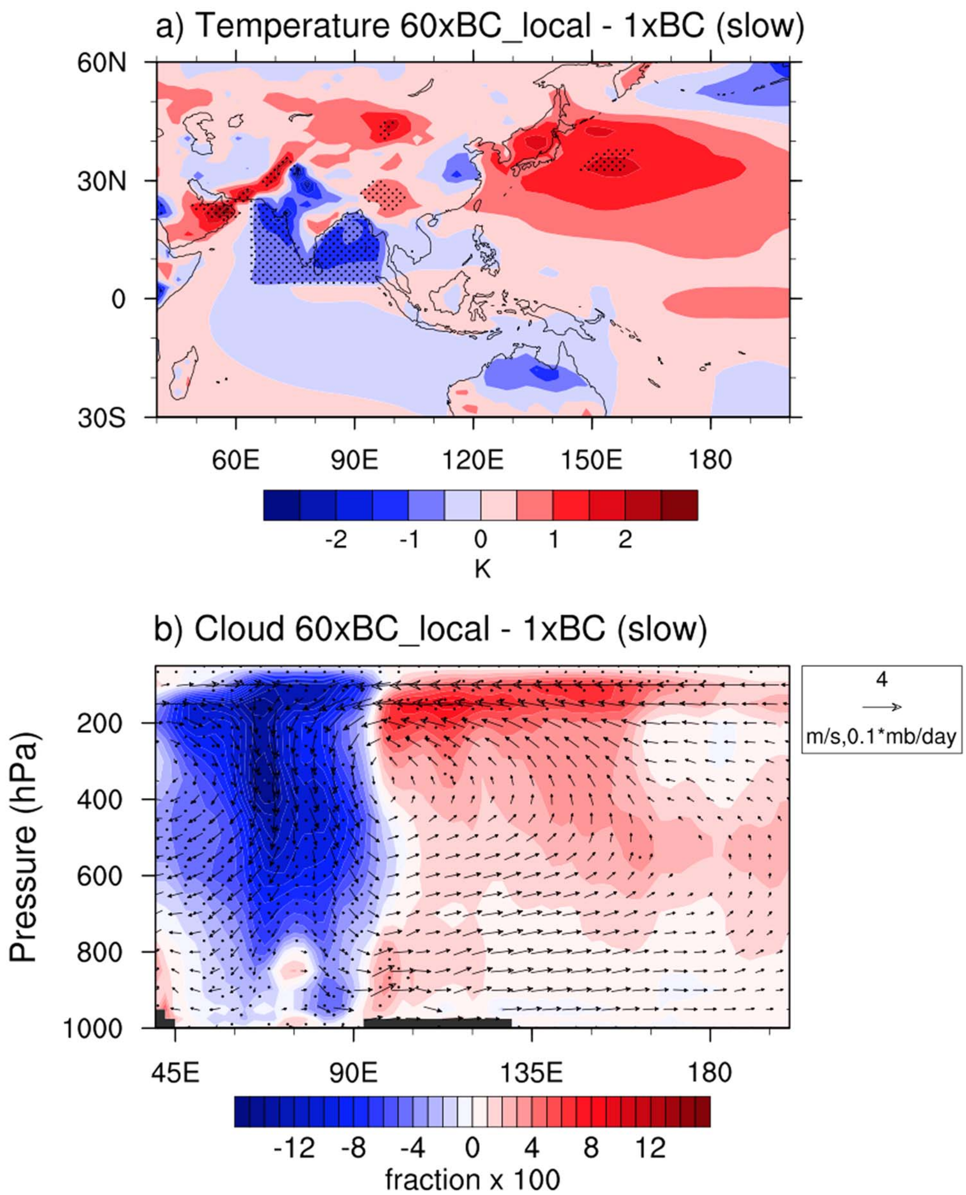

Figure 4. Spatial pattern of the slow response in June to September (JJAS) mean (a) surface temperature (K) and (b) meridionally (0° to 30°N) averaged cloudiness in the 60xBC_local case relative to the 1xBC simulation. The procedure to estimate the slow response is discussed in the text (section 3). The vectors in (b) represent the changes in circulation in the zonal direction depicted by zonal wind (u, m s^{-1}) and vertical pressure velocity (-ω, 0.1*mb day^{-1}). The stippling in the panels indicates the regions where the changes in temperature (a) and cloudiness (b) are larger than two standard deviations (confidence level of about 95%) estimated from 50 JJAS means of the 1xBC SOM experiment.

Ocean (10°S–25°N, 40°E–100°E). The estimated land-ocean temperature contrast is approximately −2.2 K during the May-June season and approximately −0.6 K during the summer monsoon season (JJAS) (figure S10). Thus, in the slow response phase, the remote aerosols lead to only a slight increase in precipitation over India (figure 1(e)).

5. Summary and conclusions

Several previous studies have assessed the impact of BC aerosols on the precipitation over India. But there is a lack of clear understanding of the relative contributions of the increase in local and remote BC aerosols. In this study, using idealized climate model simulations, we isolate the impacts of the increase in local and remote BC aerosols on the summer monsoon precipitation over India in the fast adjustment and slow response phases. We find that a 60-fold increase in the 'present-day' global distribution of BC aerosols leads to an increase in precipitation over India, which is mainly contributed by an increase in remote BC aerosols.

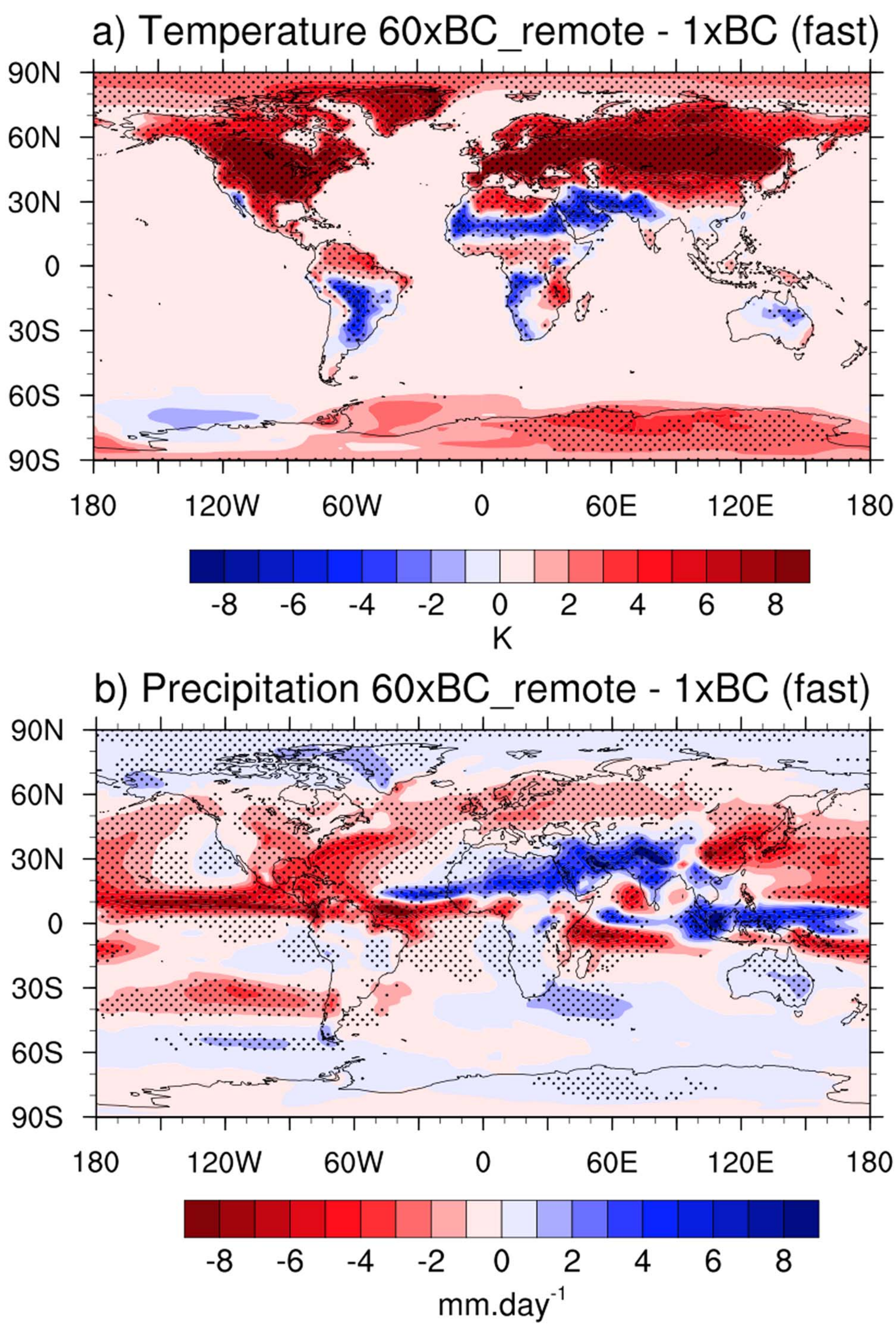

Figure 5. Spatial pattern of fast adjustments, as estimated from the prescribed-SST simulations, in June to September (JJAS) mean (a) surface temperature (K) and (b) precipitation (mm day^{-1}) in the 60xBC_remote simulation relative to the 1xBC experiment. The stippling in the panels indicates the regions where the changes are larger than two standard deviations (confidence level of about 95%) estimated from 20 JJAS means of the 1xBC prescribed-SST experiment.

For an increase in local BC aerosols, an increase in precipitation over India is simulated in the fast adjustments. Although the tropospheric warming induced by the BC aerosols increases the vertical stability in this phase, the BC-induced upper tropospheric warming near the Indo-Gangetic Plains and Tibetan Plateau and the associated enhancement in upper tropospheric meridional temperature gradient enhances cloudiness and precipitation over India. However, in the slow response phase, local BC aerosols cause a reduction in precipitation over India. In this phase, a cooling of the North Indian Ocean and a relative warming of Western Pacific triggers a Walker-cell type of circulation with downward motion, and reduced cloudiness and precipitation over India. Thus, the local BC aerosols cause an increase in precipitation over India in the fast

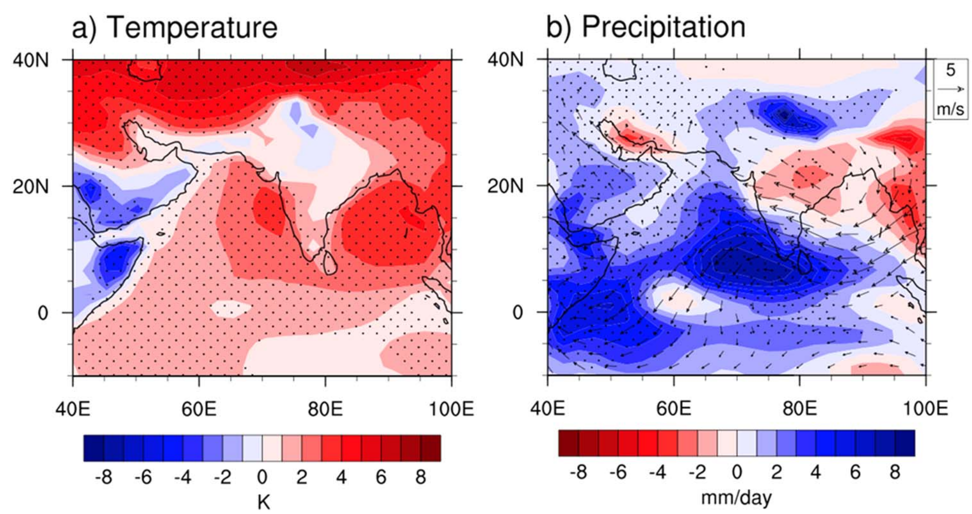

Figure 6. Spatial pattern of slow response in June to September (JJAS) mean (a) surface temperature (K) and (b) precipitation (mm day^{-1}) in the 60xBC_remote simulation relative to the 1xBC experiment. The vectors in (b) represent the changes in horizontal circulation pattern at 850 hPa pressure level. The procedure to estimate the slow response is discussed in the text (section 3). The stippling in the panels indicates the regions where the changes in temperature (a) and precipitation (b) are larger than two standard deviations (confidence level of about 95%) estimated from 50 JJAS means of the 1xBC SOM experiment.

adjustment phase, but a reduction in the slow response phase with a slightly larger magnitude, resulting in a net decline in precipitation.

For an increase in remote BC aerosols, the fast adjustments contribute to an increase in precipitation over India. In the fast adjustment phase, we find a large warming of the northern hemisphere land mass and an associated northward shift in ITCZ which enhances the precipitation over India. In the slow response phase, the increase in remote BC aerosols causes only a slight increase in precipitation over India. A decrease in precipitation is simulated over central India, which is found to be associated with a decrease in land-ocean temperature contrast. Thus, an increase in remote BC aerosols causes a net increase in precipitation over India, contributed predominantly by the fast adjustments.

There are several limitations to our study. The first limitation relates to the idealized nature of our simulations. Since the main aim of this study is to identify and disentangle the role of local and remote BC aerosols, we have performed highly idealized simulations with large increases in BC aerosols (a 60-fold increase) so that the forcing magnitude and the resulting climate response signal are larger. The spatial pattern of the increase is the same as the present-day distribution in our simulations. We believe that the idealized modeling studies like this help to understand the mechanisms more clearly than studies where the signal is overwhelmed by the climate noise. In our experiments, only the aerosol direct and semi-direct effects are included. We do not model the aerosol indirect effects in which aerosol particles act as cloud condensation nuclei and alter the cloud radiative properties. However, several studies (e.g., Bollasina *et al* 2011 and Ganguly *et al* 2012) show that the impact of aerosol indirect effects could be significant on the Indian summer monsoon precipitation. The inability of the state-of-art models to simulate the aerosol-cloud interactions realistically contributes to uncertainty in our assessment of the impacts of aerosols on South Asian summer monsoon (Li *et al* 2016). We plan to revisit the questions addressed in this study with the inclusion of the indirect effects in a future study.

We have used a slab ocean model, and hence the transient effects and deep ocean feedbacks are missing in our simulations. However, it has been shown in several studies (e.g., Danabasoglu and Gent 2009) that the magnitude of climate sensitivity does not differ significantly between slab ocean configuration and full ocean models. Even though the slab ocean models do not simulate the full ocean dynamics, they simulate the SST response to aerosol forcing realistically which is crucial for understanding the slow climate response to the effects of aerosols (Ganguly *et al* 2012). Further, our findings are based on a single model and the quantitative results could be different in other models, specifically the pattern of SST change in western Pacific in the slow response phase for an increase in local aerosols (figure 4(a)). However, since the interpretation of our major results relies on differing land-ocean response, meridional temperature gradients in the Indian Ocean region and ITCZ shift related to planetary energetics, we believe that the qualitive findings of our study would be robust across models. Further investigations using a multi-model inter-comparison framework would help to confirm the robustness of our results and assess the uncertainties.

A simple schematic and qualitative illustration to facilitate a conceptual understanding of the impact of local and remote aerosols on the summer monsoon rainfall over India inferred from this study and from the available

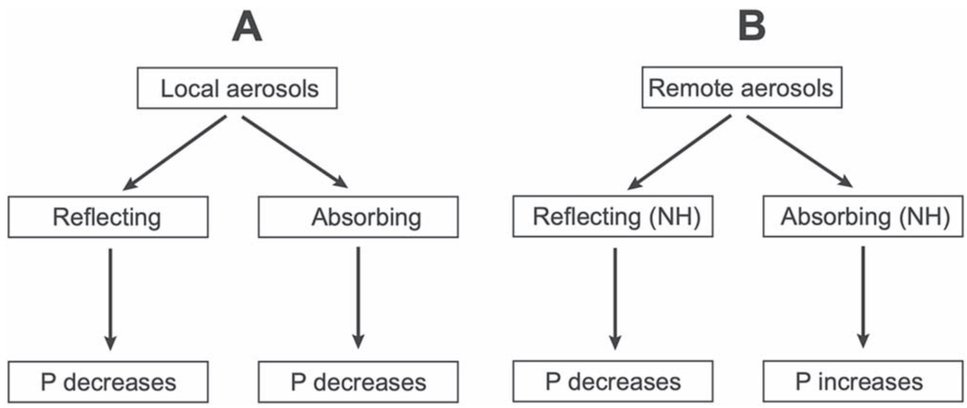

Figure 7. A schematic diagram illustrating the impact of reflecting and absorbing aerosols on the summer monsoon precipitation over India (P denotes precipitation). Section A shows the impact of local aerosols (located over India) and section B shows the impact of remote aerosols in the northern hemisphere (NH) (assuming a spatial distribution of remote aerosols that corresponds to 'present-day' distribution). The effect of remote aerosols in the southern hemisphere on Indian summer monsoon would be opposite of what is shown for remote aerosols in NH (section B).

literature is provided in figure 7. Effects of aerosols which are predominantly reflecting (e.g., sulfate) and those which are predominantly absorbing (e.g., BC) are considered. Irrespective of the aerosol's optical property, our study and the literature suggest that local aerosols lead to a decrease in precipitation over India (Ramanathan *et al* 2005, Guo *et al* 2016, section 4.3). However, the effect of an increase in remote aerosols with a near hemispherical distribution in the northern hemisphere (that resembles present-day spatial distribution) on precipitation over India will depend on the type of aerosols. The predominantly reflecting remote aerosols such as sulfates would lead to a decrease in precipitation (Guo *et al* 2016) but absorbing aerosols such as BC aerosols would lead to an increase (section 4.3, Kovilakam and Mahajan 2016, Modak and Bala 2019). The opposite effects should occur when the remote aerosols are located in the southern hemisphere with a near hemispherical distribution. This is because a near hemispherical distribution of aerosols leads to a mean hemispherical cooling (reflecting aerosols) or warming (absorbing aerosols) in the hemisphere in which the aerosols are distributed. The resulting change in interhemispheric temperature difference would cause meridional shifts in Hadley circulation and ITCZ (Donohoe *et al* 2013, Devaraju *et al* 2015, Nalam *et al* 2018) which alter the distribution of the tropical precipitation. This simpler understanding is likely valid only when the distribution of remote aerosols is nearly hemispherical as used in the study, and may not be valid for changes that are confined to specific small individual regions such as North America, Europe, China, Australia or South Africa. The investigation of the influence of such specific regional aerosol forcing on the Indian summer monsoon precipitation will require regional aerosol experiments as analyzed in Liu *et al* (2018), Persad and Caldeira (2018) and Shawki *et al* (2018) .

In summary, our model simulations show that the summer monsoon precipitation over India increases when the present-day global distribution of BC aerosol is increased. When the global increase is considered as sum of local (5°–40°N, 65°–95°E) and remote BC aerosol increases, we find that the increase in local (remote) BC aerosols in the Indian region causes a decrease (increase) in precipitation over India.

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Data availability statement

The essential dataset used for this study was uploaded by the authors to the 'Zenodo' data repository to support the findings of this paper. This data is publicly available at the link provided URL/DOI:http://doi.org/10.5281/zenodo.4578453 in the manuscript.

Conflict of interest statement

The authors declare no conflict of interest.

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