

# Response of Indian summer monsoon rainfall to remote carbonaceous aerosols at short time scales: Teleconnections and feedbacks

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## ABSTRACT

The effect of atmospheric aerosols on Indian monsoon is one of the scientifically challenging and societally relevant research issues of the recent decades. Past studies have derived inferences mostly based on local emissions and their impacts thereupon. However, more recent studies have shown that the remote effects driven by aerosols elsewhere could also impact the monsoon system on different time scales. Our study using an atmospheric general circulation model (AGCM) shows that regional carbonaceous aerosol emissions (from North America, Europe and North Africa and Asia) can significantly alter Indian summer monsoon rainfall. It is interesting to note that the effects of remote aerosols are larger and bear a resemblance to each other in comparison to local emissions. Our study reveals that the modulation of large-scale circulation induced by regional warming by carbonaceous aerosols leads to teleconnection patterns around the globe, thereby changing the precipitation depending on the phase of these disturbances. We also find that the effects of remote carbonaceous aerosols are strengthened by modulation/feedback through natural dust aerosols over the Arabian Sea with subsequent increase in rainfall over India. The results signify that the changes in the aerosol emissions in one region could lead to the change in precipitation over other regions through global teleconnection and associated feedbacks induced by regional atmospheric warming and/or cooling.

## 1. Introduction

Atmospheric aerosols have attracted wide attention due to their role in the hydrological cycle and radiative balance in a changing climate (Chung and Seinfeld, 2005; Rosenfeld et al., 2008; Myhre et al., 2017; Allen and Sherwood, 2011; Takahashi et al., 2018). The current understanding of aerosol-cloud-precipitation interaction is still limited to a moderate level (IPCC AR5). As a result, they are not well represented in the climate models and, in turn, are recognized as major source of uncertainties in the future climate projections. On the other hand, monsoon climate is characterized by seasonal reversal of prevailing wind, with successive wet and dry seasons embedded within. The interactions of monsoon forcing and responses are extremely complex, involving coupled atmosphere-ocean-land processes (Chung et al., 2002; Trenberth et al., 2005; Wang, 2006; Webster et al., 1998). Monsoon-related studies in the past have primarily focused on sea surface temperature (SST), water vapour, clouds, tropical/extra-tropical interactions, surface topography, wind dynamics and diabatic heating

processes (Dyn et al., 2017; Yun et al., 2010; Lau, 2016). However, recent studies suggest that the Indian summer monsoon (ISM) may also be modulated by aerosols (Lau and Kim, 2006; Meehl et al., 2008; Nigam and Bollasina, 2011; Sanap et al., 2015). The current hypotheses on aerosol-monsoon relationship/link are mainly through two major pathways. One is the ocean pathway, which is based on the theory that aerosol-induced surface dimming generates cooling over the ocean surface. This, in turn, weakens the meridional sea surface temperature (SST) gradient (Ramanathan et al., 2005; Eddy Chung et al., 2006; Lau and Kim, 2011; Ganguly et al., 2012a), thereby altering the circulation pattern and thus lowering monsoon rainfall. Such studies suggest that the monsoon precipitation decreases but the response induced by aerosol through ocean cooling is slow. On the other hand, the warming induced by light-absorbing aerosols in the atmosphere enhances ascending motion locally, leading to increased convergence and moisture supply and an increase in the monsoon precipitation (Lau et al., 2006; Wang et al., 2009; Lau and Kim, 2011; Kim et al., 2016; Vinoj et al., 2014; Jin et al., 2015). In this case, the pathway is through the

atmosphere (dynamics), and the response is relatively fast (shorter time scale) in comparison to the oceanic pathway. In addition, fast responses also have other mechanisms to increase South Asian monsoon precipitation, e.g., the upper-level meridional thermal gradient (Xie et al., 2020) found based on PDRMIP multi-model comparisons (Myhre et al., 2017). A brief comparison of various important studies relating aerosols to monsoon rainfall is provided in Table S1. Note that in most of these studies, the forcing and responses to these pathways are within the monsoon domain.

However, the forcing that impacts monsoon precipitation could even be remote, i.e., far away from the monsoon domain. For example, the aerosol-induced heating at one location could be transferred to another remote location via responses through the atmospheric pathway (Menon et al., 2002). Only a few recent studies (Bollasina et al., 2011; Vinoj et al., 2014; Das et al., 2015a; Ganguly et al., 2012a; Bond et al., 2013; Chakraborty et al., 2013; Jin et al., 2015; Solmon et al., 2015; Guo et al., 2016; Undorf et al., 2018) explored the remote effect of aerosols on the monsoon circulation and precipitation changes over Indian region. For example, Vinoj et al. (2014), showed the impact of natural aerosols (dust) over the North Africa, West Asia and Northern Arabian Sea on Indian monsoon rainfall, whereas Chakraborty et al. (2013), discussed the importance of remote but not source-specific forcing. Carbonaceous aerosols, including black carbon (BC) and organic carbon (OC) have been shown to affect the regional hydrological cycle of tropical monsoon regions through direct, semi-direct, and indirect effects (Jeong and Wang, 2010; Lau et al., 2006; Ramanathan et al., 2005). More details regarding aerosol-monsoon interactions are well documented in a few recent reviews (Sanap and Pandithurai, 2015; Li et al., 2016; Lau, 2016). A recent study shows net precipitation enhancement over India due to remote black carbon aerosols (Krishnamohan et al., 2021). Another study using the chemistry-climate model shows that sulphate aerosols have global impacts on rainfall irrespective of source regions (Kasoar et al., 2018).

In the present study, we investigate the impact of source-specific carbonaceous aerosols across the northern hemisphere on Indian monsoon precipitation, including their impacts over oceans adjacent to the Indian subcontinent (the Bay of Bengal and the Arabian Sea). We focus mainly on the major global source regions of carbonaceous aerosols in the Northern hemisphere using the Community Atmosphere Model version 5 (CAM 5). The details of the model configuration are provided in the subsequent section.

Please note that this study primarily aims to investigate the fast response (Bala et al., 2010; Hansen, 2005; Ganguly et al., 2012b) of monsoon precipitation to region-specific carbonaceous aerosols. Hence, we designed the experiments using prescribed Sea Surface Temperature (Hansen, 2005). However, the change in monsoon rainfall for carbonaceous aerosols induced slow response (through ocean pathways) is beyond the scope of this study and will be investigated in the future.

## 2. Study region and model configuration

We use the Community Atmosphere Model Version 5.0 (CAM5), primarily developed at the National Center for Atmospheric Research (NCAR). It includes significant enhancements to represent atmospheric processes, compared to some earlier versions of the model. The model uses a modal aerosol treatment of three size modes (Aitken, accumulation, and coarse) comprised of sea-salt, dust, sulphate, black carbon, organic carbon, and/or secondary organic aerosols. Species mass mixing ratio, as well as number concentrations, are predicted for each mode. CAM5 has the physics package for studying the direct, semi-direct, and indirect effects of aerosols (Liu et al., 2012; Ghan et al., 2012). Emissions datasets are the same as the ones used for the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) model intercomparison activities (Lamarque et al., 2010). The rapid radiative transfer method for general circulation models (RRTMG) provides radiative transfer calculations. A two-moment formulation of the microphysics

scheme is used for stratiform clouds (Gettelman et al., 2010). The optical properties of aerosols have been parameterized using the method provided by Ghan and Zaveri (2007). The optical properties of each of the aerosols are selected using the Optical Properties of Aerosols and Clouds (OPAC) datasets (Hess et al., 1998). For black carbon aerosols, the optical properties are adopted from (Bond and Bergstrom, 2006). More details of the model have been provided in some previous studies (e.g., Liu et al., 2012; Ma et al., 2013). The configuration for simulations in this study is briefly summarized in Table S2.

## 3. Experimental setup

### 3.1. Aerosol hotspots in the northern hemisphere

The present study focuses on the impact of remote carbonaceous emissions in the northern hemisphere on Indian Summer Monsoon Precipitation (ISMP). Therefore, we have perturbed carbonaceous aerosol emissions over spatially separated emission hotspots such as Northern America, Western Europe, North Africa and Asia (marked by boxes in Fig. 1). It is known that aerosols affect precipitation at different time scales, i.e., the fast and slow response depending on temporal scales and modulation of sea-surface temperatures. Here we focus on the short-term (JJA average) variability induced by carbonaceous aerosols. Therefore, we have used an AGCM (i.e., CAM5) with aerosols such as primary organic matter (POM), black carbon (BC), mineral dust, sulphate, and sea salt with the full aerosol life cycle, including emission, growth, transport, interactions with clouds, wet and dry deposition. In addition to the control run that has all aerosols included in the simulation, we perturbed carbonaceous aerosol emissions over the regions shown marked by boxes in Fig. 1. Each of these simulations was carried out for ten years (equilibrium runs), and only data during the summer period (June to August, a total of 30 months) are used for the present analysis. A total of five simulations were conducted. The details are provided in Table 1.

## 4. Results and discussion

In this section, we discuss the changes in various aerosol and other relevant meteorological parameters that affect rainfall over the Indian region. We have calculated the anomalies (CTRL minus respective experiments (experiments 1 to 4 in Table 1)) of various fields such as aerosol optical depth, single scattering albedo (Supplementary Fig. 1),

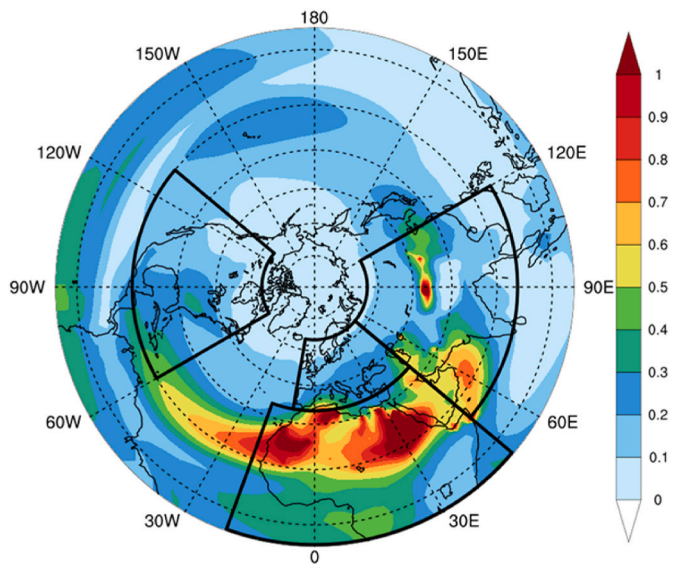


Fig. 1. Mean aerosol optical depth for June-July-August (JJA) with the boxes showing the regions where carbonaceous aerosols were perturbed.

**Table 1**  
CAM5 model experiments.

Simulations	Name	Remark/Details
Control	CTRL	Model simulation with all aerosol types
Experiment 1	NOCARB_AS	All aerosols except carbonaceous aerosols (POM, BC) over Asia (AS)
Experiment 2	NOCARB_AF	All aerosols except carbonaceous aerosols (POM, BC) over North Africa (AF)
Experiment 3	NOCARB_AM	All aerosols except carbonaceous aerosols (POM, BC) over North America (AM)
Experiment 4	NOCARB_EU	All aerosols except carbonaceous aerosols (POM, BC) over Europe (EU)

atmospheric radiative forcing, meridional and vertical winds and total (convective plus large scale) precipitation rate to explain the associated summer monsoon precipitation changes over central Indian landmass and adjacent oceanic regions. We have chosen the grid described by Goswami et al. (2006), for the central Indian region. It is to be noted that the climatological mean and variance of summer monsoon rainfall have large spatial variability across the Indian landmass. However, over the Central Indian region (Goswami et al., 2006), the mean and the standard deviation are reasonably homogeneous (spatially uniform in nature), hence being chosen for this study.

#### 4.1. Aerosol optical depth and radiative forcing

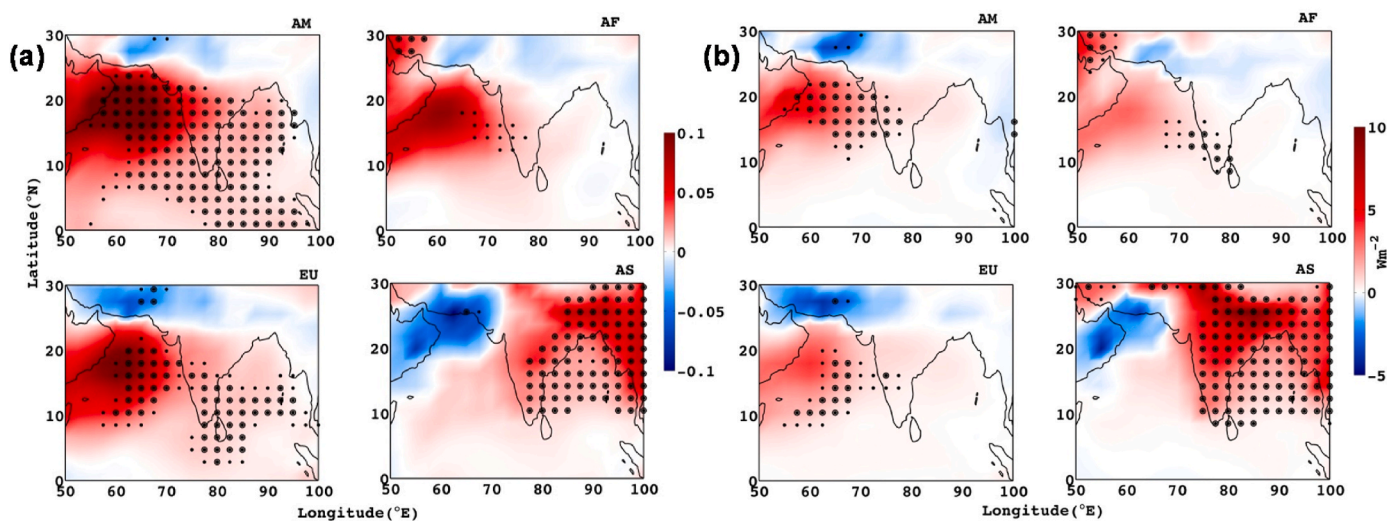
Fig. 2a shows changes in AOD over the Indian region, including the Arabian Sea and Bay of Bengal, as a result of removing emissions of carbonaceous aerosols over the different source regions. We find that for all the remote emission perturbations (North America (AM), North Africa (AF) and Europe (EU) except Asia (AS), the AOD over the Arabian Sea shows an increase (Fig. 2). On the other hand, in case of Asian emissions experiment, it is found that there is a decrease in AOD over Northern Arabian Sea, but a slight increase (not statistically significant) over the Southern Arabian Sea. The reason for the increases in AOD over the Arabian Sea may be related to the dust emission changes associated with changes to winds over the deserts surrounding the Arabian Sea (Supplementary Fig. 2). Another possibility is the increased sea-salt emissions over AS due to the increased winds (more discussions can be found in the subsequent section). It may also be due to an increase in both sea-salt and dust as a response to increased winds over the AS and adjacent regions. These aspects are further explored in subsequent sections. However, over both Indian region and to its East, AOD anomaly is

positive representing the local/regional carbonaceous aerosol loading. Note that we use the term Asian emissions or local emissions for carbonaceous aerosol emissions over the whole Asia box (Fig. 1) rather than the Indian monsoon region alone.

In addition to the aerosol loading, it is also observed that the atmospheric absorption due to aerosols have also undergone a change. It is found that the regions having an increased AOD also show a decrease in single scattering albedo (SSA, see Supplementary Fig. 1). This implies that the aerosols have become more absorbing over this region for all remote simulations except Asian perturbation. If the increase in AOD were due to increased sea salt with dust kept at the same level, the absorption would decrease rather than increase. It is to be noted that the major contributor to the increased absorption is some type of absorbing aerosols. Considering the proximity to desert regions, the maximum probability that the type of aerosol could be mineral dust.

Local carbonaceous aerosols are not expected to increase the AOD over N. Arabian Sea during the monsoon period considering the prevailing meteorology that favours the transport of either sea salt or dust from the adjacent regions towards Indian landmass. This increase in AOD and decrease in SSA can be manifested as a change to atmospheric radiative forcing through absorption.

To further explore this possibility, we have calculated the clear-sky aerosol radiative forcing at the top of the atmosphere (TOA) and at the surface. Their difference (TOA minus surface) provides the atmospheric radiative forcing (see Fig. 2b). A positive value of atmospheric radiative forcing results in a heated atmosphere and a negative value means a cooled atmosphere. The results (Fig. 2b) show a striking similarity with that of the AOD, indicating that the increased aerosols over the region are primarily of absorbing nature. Overall, there is net warming observed over the Arabian Sea, but a slight net atmospheric cooling over Central India (CI hereafter) for remote carbonaceous aerosol emissions. The result is the opposite for Asian emissions, with warming over Bay of Bengal and continental Indian landmass. It has been well established that carbonaceous aerosol or any other aerosols that may absorb radiation will lead to net atmospheric warming (Lau et al., 2006; Ramanathan et al., 2005; Sanap and Pandithurai, 2015). Local perturbation of carbonaceous aerosols over Asia can explain the simulated warming over the region of perturbation in case of Asian emissions. However, in case of remote emissions, the contribution of anthropogenic carbonaceous aerosols is quite low over this region during the monsoon period. It is interesting that carbonaceous aerosol emissions from thousands of miles away from this region (e.g., North America) could alter the aerosol loading through some teleconnection



**Fig. 2.** (a) Aerosol optical depth (AOD) anomalies (Control minus perturbed) and (b) shortwave clear-sky radiative forcing anomalies of atmosphere for all the simulations with 90% (black dots) and 95% (black circles) confidence levels for mean differences.

pattern or feedbacks. The increased warming over the Arabian Sea is most likely a consequence of changes in dust aerosols as sea salt does not absorb radiation. The absorbing nature of these aerosols over Arabian Sea as evidenced from increased absorption (atmospheric radiative forcing) may be due to increased dust loading (see [Supplementary Fig. 2](#)) which is related to the increased strength of wind speed over the adjoining region. The strengthened circulations have a potential to modulate precipitation over the Indian region through increased moisture convergence, as also shown in other studies. Past investigations using the global and regional climate model have shown that absorbing aerosols (especially dust) over the Arabian Sea play a significant role in the monsoon circulation and precipitation changes over CI ([Das et al., 2015a](#); [Jin et al., 2015](#); [Vinoj et al., 2014](#)) by initiating positive feedback of additional moisture convergence towards Central India. In our study, the perturbation is applied only to the carbonaceous aerosols in remote locations far from the monsoon domain of interest which shows the important role played by the teleconnection feedback processes initiated by the remote aerosols on Indian monsoon.

#### 4.2. Near surface winds

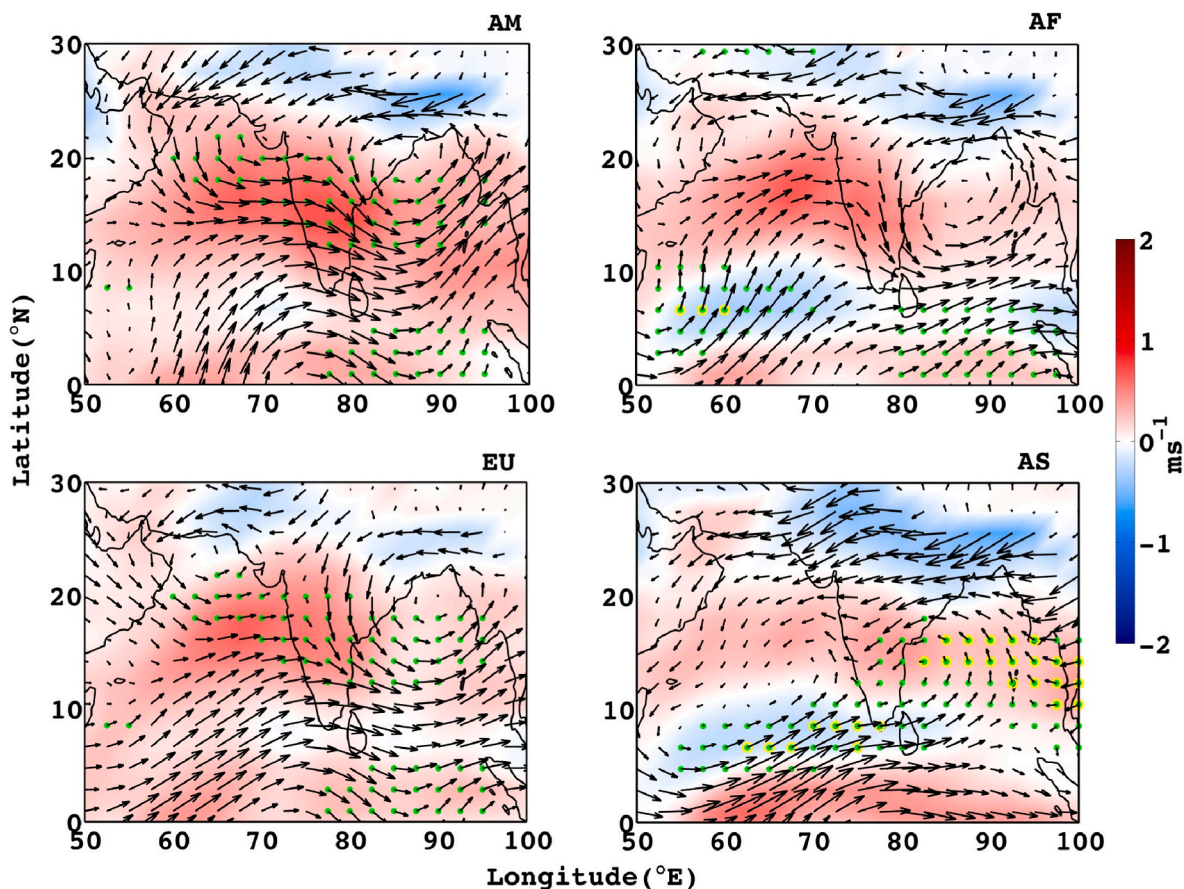
In order to see dynamical and meteorological responses due to the aerosol perturbations, we have investigated the low-level wind field (850 hPa) and precipitation anomalies in these experiments.

[Fig. 3](#) shows the winds at 850 hPa level. The coloured contours represent the anomalies of wind speeds. It is clear that the winds over Arabian Sea have increased for each of the remote perturbations, whereas the increase is smaller for the Asian emissions. Wind anomaly vectors show that the strengthened winds are directed towards the Indian landmass for the remote perturbation cases. However, the

anomalies are in opposite in the case of Asian emissions. The changes in the strength of the winds and direction indicate that there is convergence to the west and central Indian region for all the simulations; however, the spatial spread and magnitude vary. The enhanced winds are expected to increase the moisture transport from Arabian Sea towards the Indian region and hence the availability of moisture for precipitation. Studies in the past have shown that such situation leads to increased rainfall over the central Indian region ([Das et al., 2015a](#); [Jin et al., 2015](#); [Solmon et al., 2015](#); [Vinoj et al., 2014](#)). In the case of Asian perturbation, the Bay of Bengal branch of the monsoon appears to have strengthened towards Indian region whereas the Arabian Sea branch has weakened. Also, the winds over central India appear to have weakened for Asian perturbation. This shows that there is a possibility for enhanced moisture convergence from Bay of Bengal in this situation, but a reduction from the Arabian Sea branch.

#### 4.3. Precipitation anomalies

[Fig. 4](#) shows the change in precipitation over the Indian sub-continent for the different regional emission perturbations. Note that during the summer season, the precipitation is mainly liquid rain and hence we have used the word interchangeably. Similar to the earlier results for AOD and atmospheric radiative forcing, the most striking feature is the similar response of rainfall over the Indian region due to carbonaceous aerosol emissions separated spatially over the Northern Hemisphere, although the magnitude of changes is different for different regional emissions. All cases show that the rainfall increased over the Northern Arabian Sea, Bay of Bengal and Central India. However, a decrease is observed over the southern Arabian Sea for all cases except the Asian emissions. The increase (decrease) in precipitation over the



**Fig. 3.** Wind vector and wind speed (shaded) at 850 hPa with showing grids with 90% (green dots) and 95% (yellow circle) confidence levels for mean differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

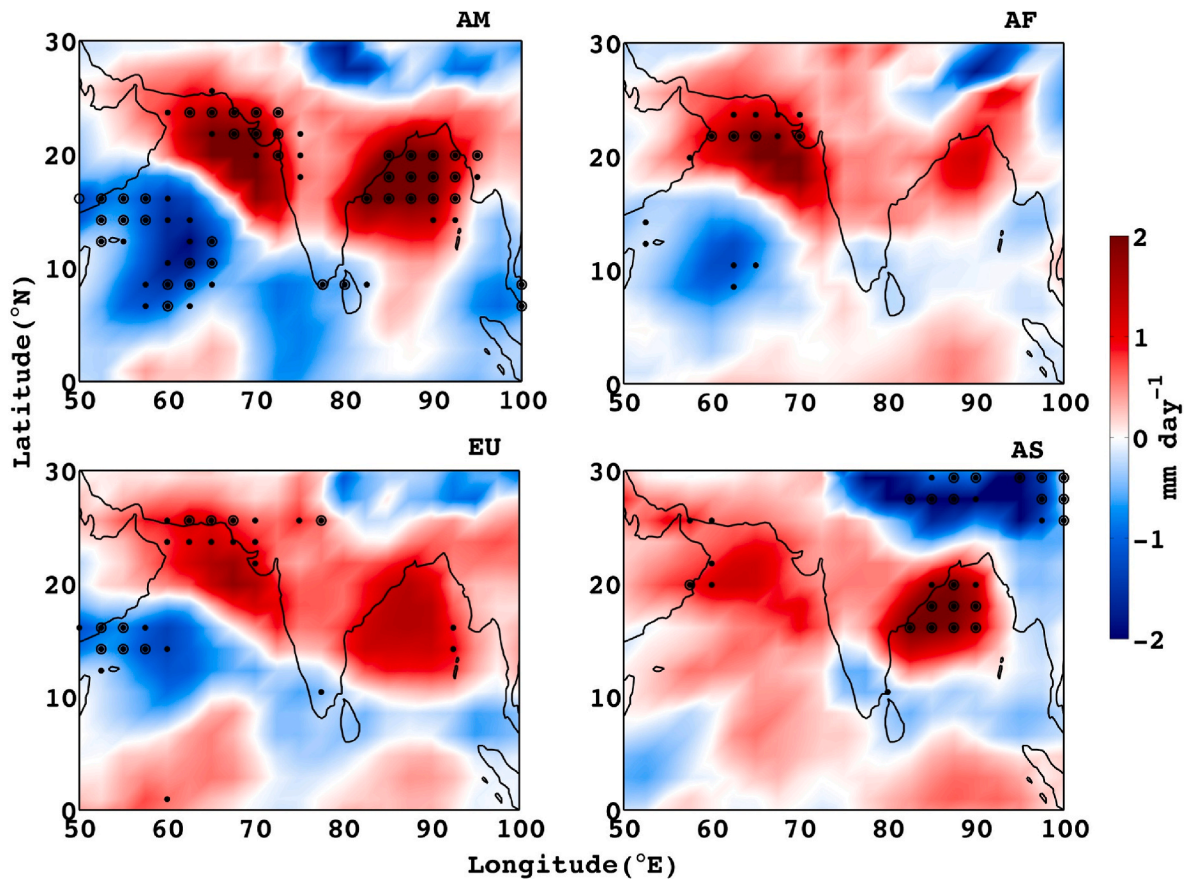


Fig. 4. Precipitation rate anomalies for all the emission perturbation experiments with black dots showing grids with 90% (black dots) and 95% (black circle) confidence levels for mean differences.

Indian region coincides with the convergence (divergence) in the lower troposphere (see Fig. 3). Similarly, the divergence observed over the southern Arabian Sea appears to be responsible for the decrease in rainfall over southern Arabian Sea. The wind anomalies over Bay of Bengal are dominated by a cyclonic circulation pattern for all simulations, thereby inducing lower-level convergence and increasing rainfall in the northern Bay. Over central India, it is found that the rainfall response is similar for all the emission cases. This is due to the similarity in the convergence/divergence patterns created irrespective of the remote emission regions.

We also quantified the area average rainfall over central India and adjacent oceans (5°-22°N and 85° to 92°E for the Bay of Bengal; 5°-22°N and 50° to 70°E for the Arabian Sea) to discern the rainfall changes as a response to carbonaceous aerosol perturbation within Asia and over remote regions of North America, North Africa and Europe (see Fig. 5). As discussed earlier, it is found that carbonaceous aerosols increase rainfall over the Indian region irrespective of the geographical region of their emissions considered in this study. The remote effect except Asia appears to be dominant over the central Indian region with a change as high as 1.5 mm/day (>20% with respect to mean rainfall). The precipitation response and its magnitude are mostly driven by the changes to the magnitude of winds and their direction over the Arabian Sea. This observation reinstates our understanding that any perturbation that may induce a change to Arabian Sea winds could eventually modulate monsoon rainfall.

The average rainfall changes are higher over central Indian landmass when compared to the adjacent oceanic regions. This is mainly due to the averaging over the whole domain, which also includes reduced rainfall to the south of these ocean basins. It is also found that there exists a North-West to South-East pattern of increased rainfall covering

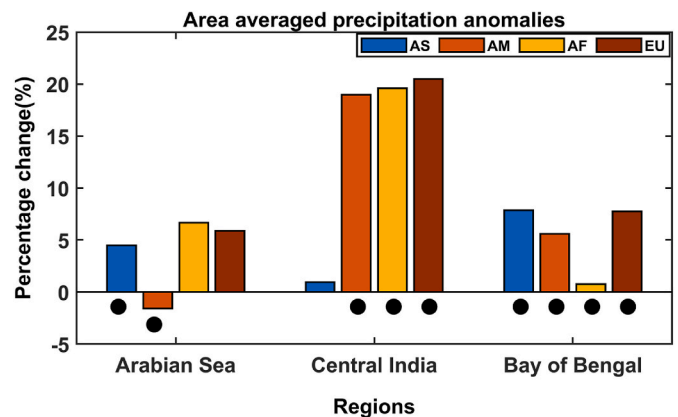


Fig. 5. Precipitation anomalies over Indian monsoon domains for all the emission perturbation experiments. Black markers indicate the results which are significant at 95% confidence level using student's t-test for mean differences.

the Northern Arabian Sea, Central Indian landmass and Northern Bay of Bengal, where there is an increased rainfall. Whereas south of this band is a region of decreased rainfall, most intense over the Arabian Sea. This is also the reason why the total rainfall changes over the Arabian Sea are lower than that over Bay of Bengal.

Our study shows that carbonaceous aerosols, specifically over different emission regions within the Northern Hemisphere could modulate precipitation over the Indian region. Also, these remote carbonaceous aerosol impacts are more significant than those compared

to Asian emissions that also include India. The response to remote emissions other than Asia is further enhanced over the land due to possible feedbacks of dust aerosol loading over the Arabian Sea. One of the interesting questions that arise from the responses discussed in the earlier sections is, what causes the impacts to be similar in terms of changes to AOD, atmospheric forcing, winds, rainfall etc. To answer this, we explore the 200 hPa winds and associated changes to vertical velocity anomalies.

#### 4.4. Upper-level wind anomalies

Investigations in the past have made the connections between upper tropospheric waves with Indian and Asian monsoon (Joseph and Srinivasan, 1999; Yun et al., 2010; Chakraborty et al., 2013; Bartlett et al., 2018; Yadav et al., 2018; Lau et al., 2020). It is shown that the planetary wave activities at ~200 hPa levels during summertime over Indian longitudes have a strong correlation with the ISM rainfall (Hu et al., 2005; Ding and Wang, 2007) and is best represented by meridional winds at that level. We investigate the aerosol induced changes to 200 hPa meridional wind anomalies over the globe. The anomalies resemble a structure similar to stationary Rossby waves observed by the previous studies (Joseph and Srinivasan, 1999; Hu et al., 2005; Ding and Wang, 2007). The changes in the phase of upper tropospheric Rossby waves using the meridional wind anomalies as a proxy are shown in Fig. 6. It is seen that perturbations over different regions result in similar anomalous meridional wind pattern over the Indian region, except for Asian perturbations. Fig. 6 (global) & 7 (zoomed over the study region) show the mean JJA meridional wind anomalies of 200 hPa. It can be observed that the aerosol-induced heating and responses thereupon create a wave train response that induces anomalous northerlies winds over the Indian region and southerlies over the west Asian region. This resulting anti-cyclonic circulation at the upper level is known to be associated with the surface cyclonic vorticity that strengthens the monsoon (e.g.

Joseph and Srinivasan, 1999). The consequent increased moisture transport towards the land leads to enhanced rainfall. It is clear that the remote emissions irrespective of their location enhance moisture transport over the Indian land mass especially the central India with potential for enhanced precipitation. On the other hand, Asian emissions experiment shows a reduced magnitude of this Rossby wave response over the monsoon domain. This is clearly reflected in the reduced enhancement of precipitation over the Indian region (more discussion in section 5).

#### 4.5. Mean vertical pressure velocity

Fig. 8 shows the anomalies of vertical pressure velocity (averaged over latitude 5°N to 30°N). Pressure velocity indicates areas of large-scale rising (blue) and sinking (red) motion. Rising air (blue) often indicates regions of low pressure. With adequate moisture availability and favourable environmental conditions, low pressure results in rising air and precipitation. Sinking air (red) often indicates regions of high pressure. The results show a good agreement with the changes discussed in section 4.4. In the cases of remote emissions, there is clearly a strong anomalous upward motion over the longitudinal band covering the Indian landmass except for Asian emissions. However, over oceanic regions of BoB, the resultant vertical velocity anomaly (control minus perturbed) is mostly downward at lower levels suppressing moisture transport to the free troposphere, thereby impacting rainfall. This shows that perturbations in remote aerosols may result in changes to atmospheric stability over the Indian region affecting vertical motions, and ultimately resulting in changes to the monsoon rainfall.

### 5. Summary and conclusion

An AGCM (CAM 5) is used to investigate the possible impacts of carbonaceous aerosol emissions from regions such as North America,

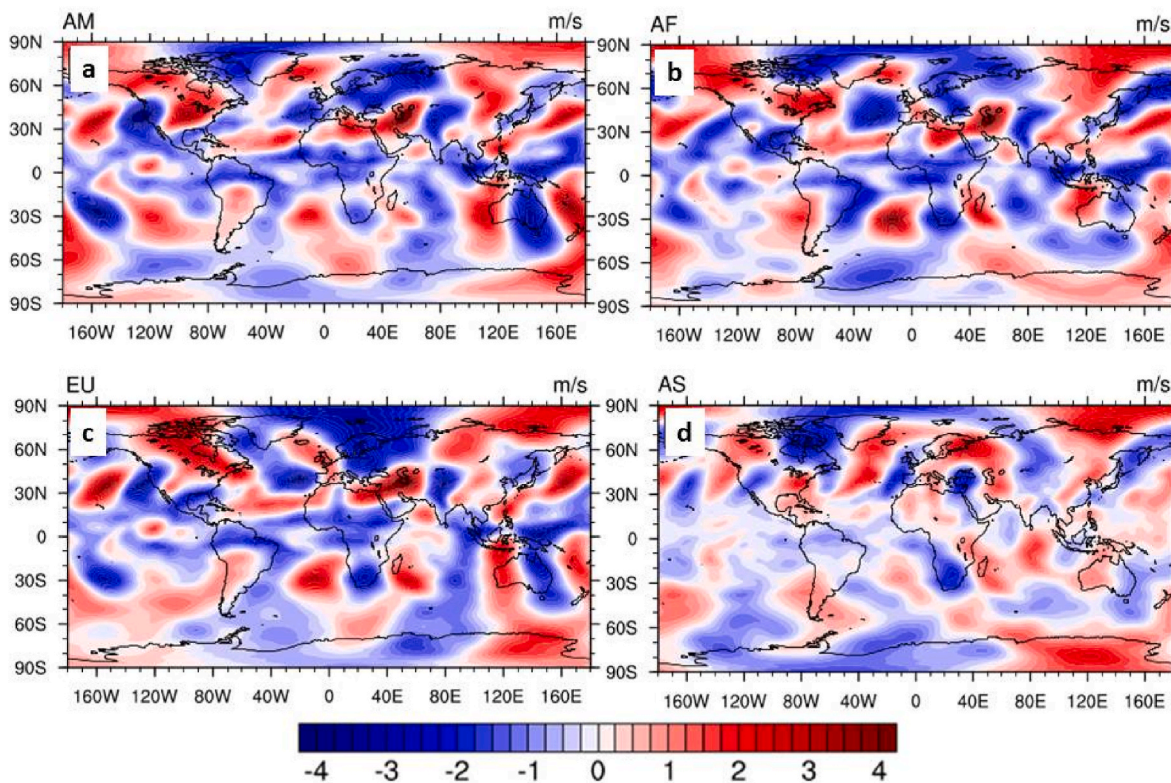


Fig. 6. 200 hPa Meridional wind anomalies for all the emission perturbation experiments showing cyclonic (red) and anti-cyclonic (blue) patterns. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

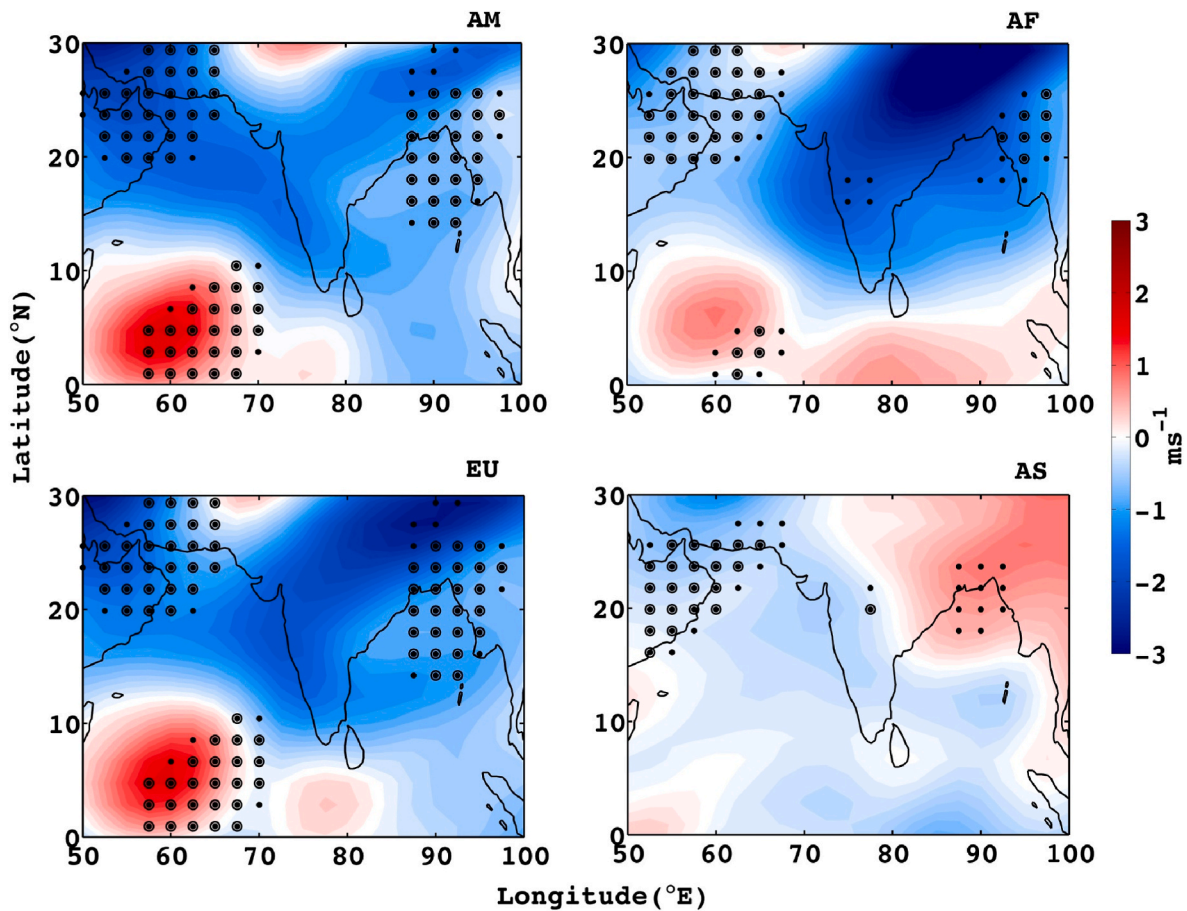


Fig. 7. 200 hPa meridional wind anomalies (zoomed over the area of interest) for all the emission perturbation experiments showing cyclonic (red) and anti-cyclonic (blue) patterns with 90% (black dots) and 95% (black circles) confidence levels for mean differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

North Africa, Europe and Asia to Indian summer monsoon precipitation. Our study shows that the remote carbonaceous aerosols induce changes in planetary Rossby wave patterns in the upper atmosphere that are observable in meridional wind anomalies. These patterns induce similar divergence/convergence over the Indian landmass and the adjacent oceanic regions. In addition, the convergence and divergence patterns also lead to increased dust aerosol loading over the Arabian Sea, thus altering surface winds and hence moisture convergence over the Indian landmass. This is a response to the remote carbonaceous aerosol perturbations combined with potential positive feedback that enhances the strength of moisture convergence over the Arabian Sea and increases rainfall over the Indian region, as also suggested by several earlier studies (Das et al., 2015a,b; Jin et al., 2014, 2015; Lau et al., 2020; Vinoj et al., 2014).

It is noteworthy that especially for Asian aerosol emission, many recent studies have highlighted the BC and dust induced snow darkening effect (SDE) over the Tibetan Plateau (TP) region (Das et al., 2020; Xie et al., 2020). Individually or along with the direct aerosol effect, SDE can substantially influence the Asian climate, including the South Asian monsoon system (Das et al., 2020; Qian et al., 2011; Shi et al., 2018; Xie et al., 2018, 2020). Hence the observed insignificant enhancements in ISMP for Asian emission changes, compared to other regional emissions, are likely due to the competition of the snow-darkening effect and direct effect. Please note that isolating the effect of carbonaceous aerosol induced snow darkening effect on ISMR from total effects is beyond the scope of this study. We aim to perform additional experiments considering BC direct and snow-darkening effects separately to solve this problem in the future.

In short, this study provides insight into how changing carbonaceous emissions elsewhere could impact Indian monsoon rainfall through atmospheric pathways.

In summary, our study, for the first time, shows that.

1. The response of Indian summer monsoon precipitation to region-specific remote carbonaceous aerosols (North America, North Africa and Europe) is similar in nature. These similarities were observed in AOD, atmospheric radiative forcing, winds (in both lower and upper troposphere), divergence/convergence patterns and subsequent rainfall.
2. The remote carbonaceous aerosol induced change in JJA rainfall over the Indian region could be as large as 20%, as a consequence of positive feedback within the monsoon domain.
3. The modulation of rainfall by different emission sources appears to be a consequence of wave-like disturbances coupled with associated changes to convergence/divergence in the upper atmosphere wind anomalies.
4. The remote carbonaceous aerosols induce surface (upper) convergence (divergence) over the landmass and vice versa over the adjacent oceanic regions.
5. Circulation changes further induce absorbing aerosols load (primarily dust) over the Arabian Sea. This led to additional moisture convergence towards the Indian landmass by warming the atmosphere hence plays as positive feedback to central Indian precipitation.

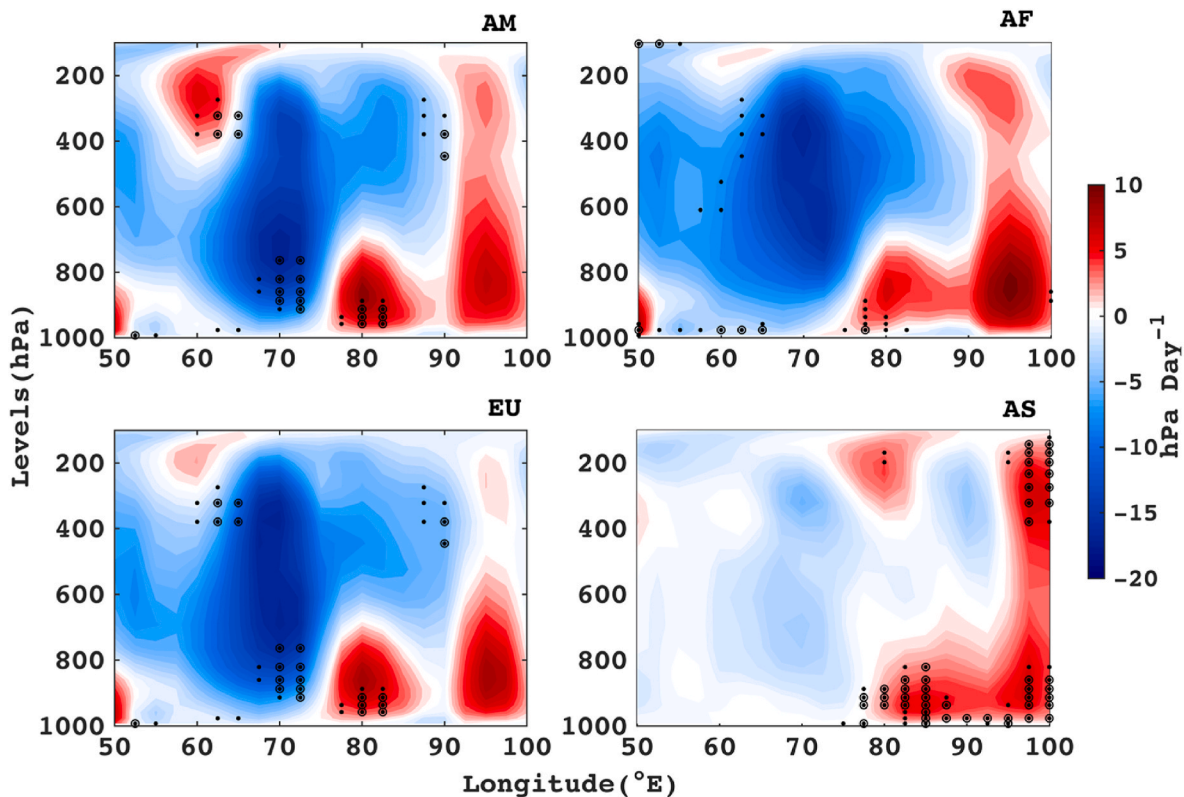


Fig. 8. Change in JJA means vertical pressure velocity (averaged over latitude 5° N to 30° N) for all the simulations with 90% (black dots) and 95% (black circles) confidence levels using the student's t-test for mean differences.

#### Data and code availability

The simulations used for this study and codes for analysis are available from the corresponding author upon reasonable request.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2022.113898>.

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