Review Article

Aerosols and Their Influence on Indian Monsoon Rainfall

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Abstract

The Indian Monsoon Rainfall, vital for the livelihoods of over a billion people, is significantly influenced by aerosols. This study examines the impacts of local and remote aerosols on Indian monsoon rainfall using advanced climate models. Absorbing aerosols, such as black carbon and dust, enhance pre-monsoon warming and early-season rainfall but suppress peak monsoon precipitation through weakened convection and stabilized land-sea thermal gradients. Remote aerosols, particularly from East Asia, alter interhemispheric temperature gradients and redistribute precipitation via cross-equatorial energy transport. Aerosols also counteract greenhouse gas-induced monsoon intensification, revealing a complex interplay of anthropogenic forcings. These findings highlight the dual role of aerosols in modulating monsoon variability and underscore the need for improved observations and modeling to refine projections. This research provides critical insights to mitigate socio-economic risks and manage air quality and climate challenges in monsoon-dependent regions.

1. Introduction

The South Asian monsoon is a cornerstone of regional climate, delivering over 80% of annual rainfall and sustaining the livelihoods of more than a billion people. This rainfall is essential for agriculture, water resources, and socio-economic stability across South Asia. The monsoon system is governed by the seasonal migration of the Intertropical Convergence Zone (ITCZ), driven by interhemispheric temperature gradients. However, significant changes in monsoon rainfall patterns, particularly a decline during the late 20th century, have raised concerns about the role of anthropogenic influences, especially aerosols, in modulating monsoon dynamics.

Atmospheric aerosols, produced primarily by industrial activity, transportation, and biomass burning, have emerged as critical drivers of monsoon variability. Scattering aerosols, such as sulfates and nitrates, cool the surface by reflecting solar radiation, while absorbing aerosols like black carbon and dust warm the atmosphere by trapping solar radiation. This duality disrupts the land-sea thermal contrast—a key driver of monsoon circulation—weakening monsoon rainfall. The "semi-direct effect," wherein absorbing aerosols promote cloud evaporation and suppress cloud formation, further exacerbates these impacts.

South Asia's rapid industrialization since the 1950s has led to significant increases in aerosol emissions, with regions like the Indo-Gangetic Plain becoming global hotspots of aerosol optical depth (AOD). While local aerosols exert substantial influence on monsoon rainfall, remote aerosols from regions like East Asia also play a pivotal role by altering large-scale atmospheric circulation and shifting the ITCZ. Recent studies highlight the interconnected nature of local and remote aerosol effects, emphasizing their role in driving monsoon variability through direct radiative effects and indirect interactions with clouds.

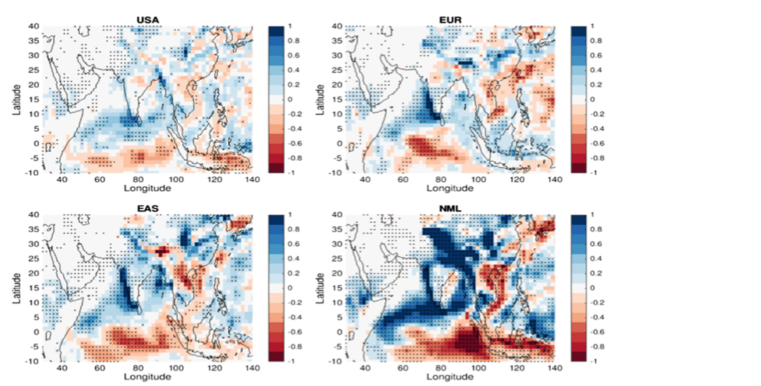
The Indian subcontinent and surrounding regions are subject to heavy loading of absorbing aerosols, i.e., dust and black carbon, which possess spatial and temporal variability that are closely linked to those of the Asian monsoon water cycle[1]. According to IPCC 5th assessment report, current understanding of aerosol–cloud–precipitation interaction is low to moderate, as a result they are not well represented in the climate models, and in turn are recognized as major uncertainties in the future climate projections[2]. In South Asian monsoon regions, the aerosol forcing response to water cycle is even more complicated. Substantial amount of transported dust from Middle East countries and adjacent deserts get accumulated over Indian subcontinent (mainly North India and Indo Gangetic Plains; IGP) and further coated with black carbon (BC) produced from local emission, which make the atmospheric physics and chemistry of the aerosol more complex over the region [6] [1].

Despite advances in modeling, the precise mechanisms and relative contributions of local versus remote aerosols remain poorly understood. This study leverages the existing information of state-of-the-art climate models and refined experimental setups to summarize the complexities of aerosol-monsoon interactions.

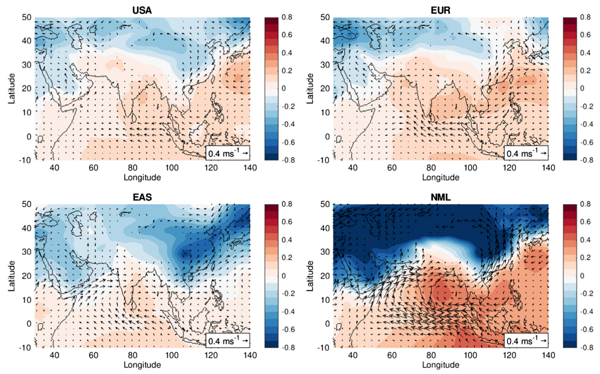
2. Results and Discussion

2.1. Influence of regional sulfate aerosols on South Asian Monsoon

Five scenarios were designed using the HadGEM3-GA4 coupled climate model to evaluate the influence of regional sulfate aerosol emissions on South Asian monsoon precipitation : (1) complete removal of anthropogenic SO emissions over the entire northern midlatitudes (NML), representing the combined impact of emissions from East Asia, the United States, and Europe; (2) removal of SO emissions specifically over East Asia (EAS); (3) removal of SO emissions over the United States (USA); (4) removal of SO emissions over Europe (EUR); and (5) a control simulation (CTL), where all emissions were set to present-day (2000) levels. These experiments isolated the regional contributions of SO emissions while maintaining the emissions of other gases and aerosols at baseline levels. The design allowed for assessing the distinct and cumulative effects of regional emissions on precipitation patterns, interhemispheric temperature gradients, and monsoon dynamics. It has been observed that sulfate aerosol reductions across different midlatitude regions, including the United States (USA), Europe (EUR), and East Asia (EAS), produce a consistent increase in South Asian precipitation as shown in 4a, primarily through interhemispheric temperature gradients and associated moisture transport mechanisms. East Asia's emissions emerged as the dominant contributor to monsoon changes, driven by strong regional land-sea thermal contrasts and sea-level pressure anomalies, which significantly influenced monsoon circulation. The removal of East Asian emissions led to the most substantial hydrological sensitivity due to its geographical proximity and greater influence on land-sea contrasts. 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 as can be seen in 4b. 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. Overall, the key message is



(a) The 150-year June–July–August mean precipitation (mm/day) response due to removing SO2 emissions from USA, EUR, EAS, and NML in fully coupled ocean-atmosphere simulations.



(b) The 150-year JJA mean 850-hPa wind changes (m/s) and shaded contours of sea level pressure (hPa) response when removing SO2 emissions from USA, EUR, EAS, and NML.

Figure 1. Precipitation, wind and sea level pressure response when removing SO2 emmisions from some specific regions.

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[7].

2.2. Elevated Heat Pump hypothesis

Dust aerosols transported from deserts of east and southeast Asia (Pakistan/Afghanistan, Middle East, Sahara, and Taklamakan) towards India induces heating during pre-monsoon (April-May) additionally north India is reinforced by the heavy loading of black carbon from industrial pollution Indo-Gangatic Plain and northern India. This elevates against the southern and northern slopes of the Tibetan Plateau (TP), during April through May. The deep convection forces the enhanced upward motion which further heats up the troposphere through release in latent heat of condensation, leads to enhanced local meridional circulation with rising motion over northern India and foothills of Himalayas and sinking motion over Northern Indian Ocean. Once the monsoon sets in over Indian region, aerosol loading reduces due to rainout and wash out, but anomalous deep convection, which set up in May continues to amplify and strengthen the meridional overturning circulation through release of latent heat of condensation. onal overturning through releasing heat of condensation. The EHP essentially holds that absorbing aerosols accelerate physical processes that contribute to the late spring and early summer heating of the troposphere over the Tropics, which is well known to have a strong impact on the evolution of the Asian monsoon[1][6].

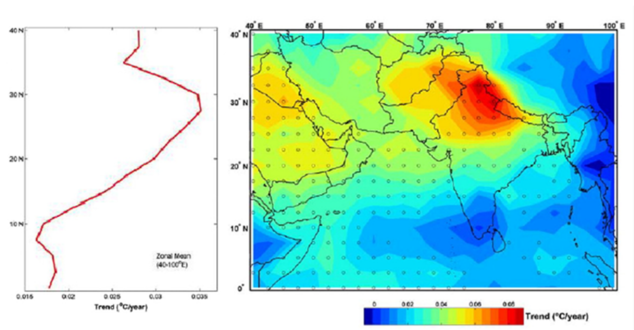


Figure 2. Zonal mean (40–100E) latitudinal profile of mid-tropospheric temperature trend along with spatial distribution of temperature trend over the Indian Monsoon region for the pre-monsoon season (March–April–May) from 1979 to 2007.[6]

Results with respect to EHP effect are consistent in showing that the anomalous high concentration of absorbing aerosol during the pre-monsoon season is associated with a) anomalous warming associated with the development of a large-scale anticyclone in the upper troposphere over the Tibetan Plateau in May and June, b) an advancement of the monsoon season, with increased rainfall coming to northern India during May, and c) subsequent enhancement of the monsoon rain over India in June–July. Although the present analysis is focused on seasonal-to-interannual time scale, the relationships shown may also hold on decadal to climate change time scales reflecting the increased loading of the black carbon from anthropogenic sources in the IGB.

There are also severel drawbacks in this field. The uncertainties in estimating the climate sensitivity of the anthropogenic aerosols are high in experimental as well as modeling approaches. Aerosol observations do not have a dense network to provide appropriate spatial distribution. On the other hand satellite observations are not able to quantify the anthropogenic and natural emission, but can provide the large scale spatial distribution. Therefore, increasing the number of observational sites, identifying and minimizing the uncertainties related to aerosol distribution, transport and effects remains a constant task in the field along with development of highly capable models of field.

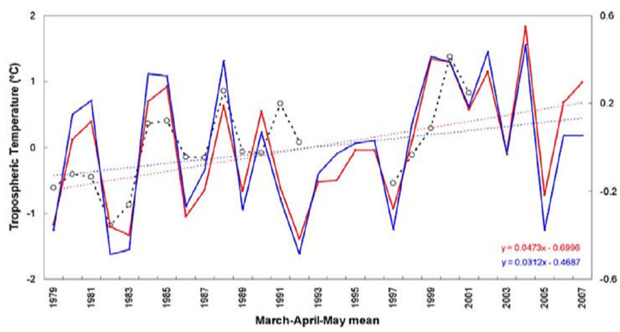
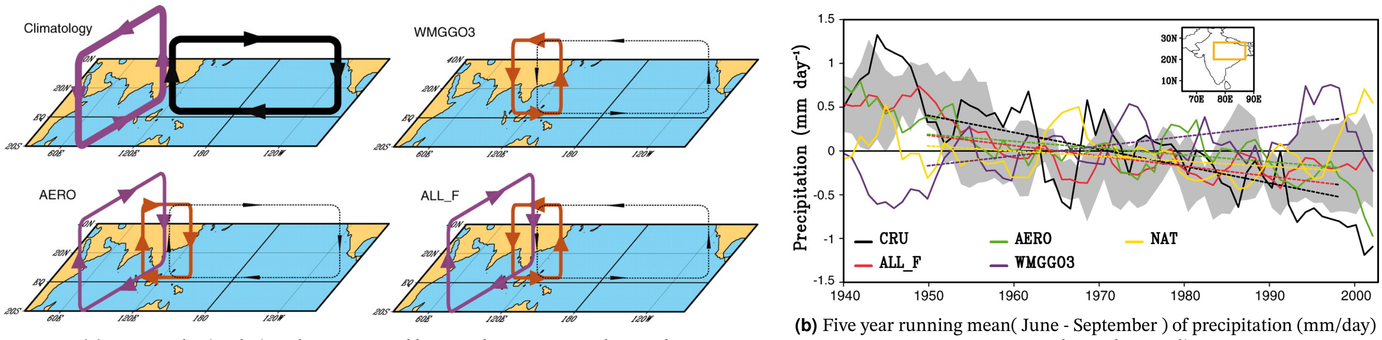


Figure 3. Red and blue curves(solid)show inter-annual variations of temperatures in the middle (4–7km)and lower (surface-4km)troposphere, respectively, over northern India for MAM period (mean) from 1979 to 2007. Straight lines (dotted) indicate the linear trends. TOMS Aerosol Index variations during MAM over northern India since 1979 are shown by black dashed curve.[6]

2.3. Aerosols and Greenhouse Gases

Using the NOAA GFDL CM3 global climate model, long-term climate trends for the period 1951–1999 were analyzed under specific forcing scenarios: WMGGO3, isolating the effects of greenhouse gases (GHGs) and ozone, and AERO, isolating the effects of aerosols. The findings underscore the divergent impacts of these forcing agents on South Asian monsoon dynamics and precipitation patterns.

The AERO scenario revealed that aerosols play a dominant role in driving drying trends over central-northern India. By reducing



(a) Large scale circulation changes caused by greenhouse gases and aerosols.

(b) Five year running mean(June - September) of precipitation (mm/day) over central - northern India

Figure 4. Large scale circulation by greenhouse gases along with five year running mean of precipitation (mm/day) [4]

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land-ocean thermal contrasts and weakening large-scale monsoon circulation, aerosols inhibit atmospheric ascent, thereby reducing precipitation. This contrasts with the WMGGO3 scenario, which indicates wetter conditions driven by GHG-induced atmospheric warming and enhanced moisture availability. The aerosols' influence effectively counteracts the GHG-driven trends, showcasing their critical role in modulating regional climate dynamics.

While GHGs contribute to increased monsoon intensity, aerosols offset these effects by altering the thermal and circulation dynamics of the region. The study emphasizes the necessity of incorporating both aerosol and GHG forcings into climate models for accurate projections of monsoon trends under future climate scenarios[4] Fig.4a Fig.4b.

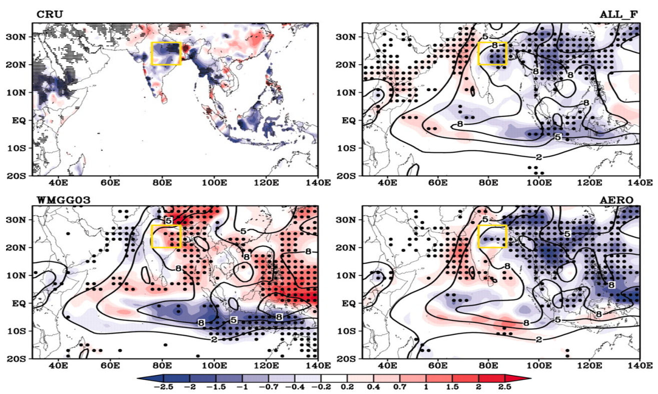

Figure 5. Spatial pattern of 1950 -1999 least squares linear trends of the June - September average precipitation[4]

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August declines, partially offsetting the early-season increase. The stabilization of the land-sea temperature gradient during the peak monsoon period exacerbates this reduction, with warming south of 10°N suppressing monsoonal activity relative to the northern landmass. These findings highlight the dual role of aerosols in modulating ISMR, enhancing early-season rainfall while dampening peak monsoon activity. This complex interplay underscores the importance of incorporating aerosol dynamics into models to improve predictions of monsoon variability under changing climatic conditions[3] Fig.8.

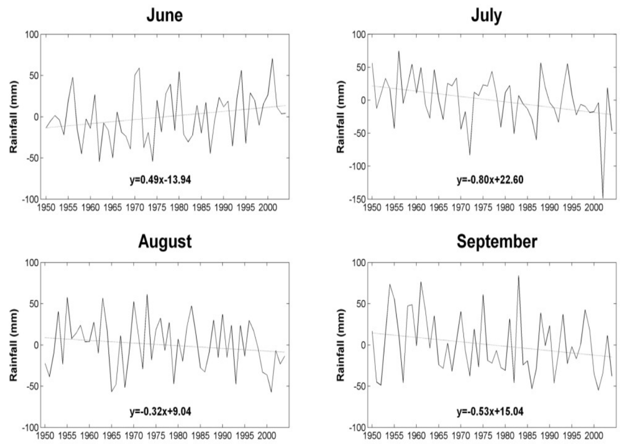

Figure 6. Time series and linear trends of monthly separated monsoon rainfalls [3]

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2.4. Interannual variability of ISMR due to aerosols

A marked increase in early monsoon rainfall, particularly in June, has been observed in the interannual variability in Indian Summer Monsoon Rainfall (ISMR) influenced by aerosols, with rates rising by 0.77 mm/year since the 1950s—representing a 20% increase relative to the long-term mean. This early-season enhancement is driven by the strengthening of the pre-monsoon land-sea tropospheric temperature gradient, attributed to sustained warming over the Himalayan-Gangetic region. Aerosols such as black carbon and dust intensify this warming through solar absorption, amplifying meridional circulation and enhancing moisture transport from the Arabian Sea. Declining Himalayan snow cover and strengthening sea surface winds further contribute to increased moisture influx, as evidenced by spatial rainfall trends showing strong increases over the Arabian Sea and Bay of Bengal.

In contrast, the peak monsoon months (July–September) exhibit an overall reduction in precipitation. This decline is linked to atmosphere-land feedback mechanisms, where intense early-season rainfall cools the land surface, weakening the thermal gradient necessary for sustained convection. As a result, rainfall during July and

2.5. Impact of local and remote aerosols on South Asian Monsoon precipitation and temperature

Three climate simulations were performed using the NOAA GFDL CM3 model to investigate the distinct roles of local and remote anthropogenic aerosols in modulating South Asian monsoon precipitation and temperature: The ALLF (All Forcing) simulation incorporated all natural and anthropogenic forcings for the period 1950–1999, representing real-world conditions. The PI-SA (Preindustrial South Asian Aerosols) simulation fixed South Asian aerosol emissions at preindustrial levels while allowing other forcings to evolve, isolating the influence of local aerosols. The PI-RW (Preindustrial Remote Aerosols) simulation fixed non-South Asian aerosol emissions at preindustrial levels, focusing on the effects of remote aerosols.

The results revealed that local aerosols play a dominant role in suppressing monsoon rainfall. The ALLF simulation showed significant drying over central and northern India, consistent with observed late 20th-century weakening of the South Asian monsoon. However, in the PI-SA simulation, fixing South Asian aerosols at preindustrial levels reversed this drying and led to wetter conditions over central India. This effect was attributed to the cooling influence of local

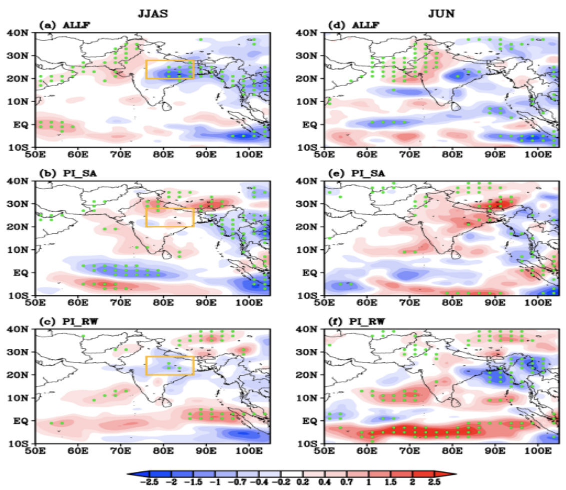

Figure 7. Spatial pattern of 1950 -1999 least squares linear trends of the June - September average precipitation[5]

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aerosols, which diminishes the land-sea thermal gradient, weakens monsoon circulation, and reduces precipitation. In contrast, the PI-RW simulation showed a more nuanced impact of remote aerosols. Fixing remote aerosols resulted in slight drying over northern India but increased rainfall over northwestern India and the Indian Ocean. These spatial variations were linked to changes in cross-equatorial energy transport and modifications to monsoon winds, highlighting the complex role of remote aerosols in redistributing precipitation patterns.

Temperature responses further elucidated the role of aerosols in driving monsoon variability. The ALLF simulation revealed widespread surface cooling over South Asia due to aerosols' dimming effect, which offsets greenhouse gas warming and contributes to weakened monsoon circulation. Fixing remote aerosols in the PI-RW simulation caused significant warming across South Asia, underscoring their substantial cooling influence in the ALLF scenario. These temperature changes disrupted atmospheric pressure gradients, further influencing monsoon dynamics.

Local aerosols primarily suppress rainfall through regional cooling, while remote aerosols alter temperature gradients and cross-equatorial energy transport, reshaping precipitation patterns and influencing the monsoon system's broader dynamics[5].

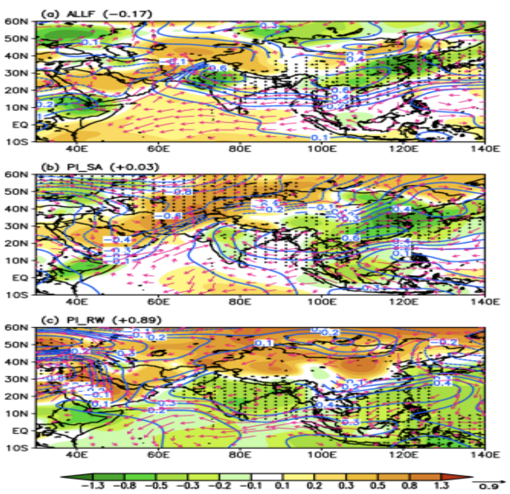

Figure 8. Spatial pattern of 1950 -1999 least squares linear trends of the June - September average precipitation[5]

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3. Conclusion

This article examines the complex role of aerosols in shaping Indian monsoon rainfall patterns, with a focus on the relationship between local and remote aerosol emissions. This article highlights the dual impact of aerosols on the monsoon system—enhancing early-season rainfall while suppressing peak monsoon activity. Local aerosols, particularly black carbon and dust, emerge as dominant factors in modulating monsoon dynamics. These aerosols cool the land surface, weakening the land-sea thermal contrast and reducing precipitation during the monsoon peak. Conversely, their pre-monsoon warming effect intensifies meridional circulation, increasing early-season rainfall. Remote aerosols, notably from East Asia, further influence the monsoon by altering interhemispheric temperature gradients, shifting the ITCZ, and redistributing precipitation patterns. Absorbing aerosols such as black carbon amplify regional warming, fostering anomalous circulation patterns that modulate rainfall spatially and temporally. Meanwhile, the competing effects of greenhouse gases and aerosols reveal a delicate balance, with aerosols counteracting GHG-induced intensification of the monsoon.

This article reinforces the critical need for integrated observational and modeling approaches to improve projections of monsoon variability under changing climatic conditions. Addressing the uncertainties in aerosol dynamics, particularly their regional and seasonal impacts, remains essential. Insights from this study provide valuable guidance for climate mitigation strategies and emphasize the importance of international collaboration to regulate both local and remote aerosol emissions. These efforts are crucial for sustaining the socio-economic stability of South Asia, a region heavily reliant on the monsoon for its water and food security.

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