Short-term modulation of Indian summer monsoon rainfall by West Asian dust

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Abstract

The Indian summer monsoon results from a complex interplay between radiative heating, dynamics, and cloud-aerosol interactions. Despite increased scientific attention, the effect of aerosols on monsoons still remains uncertain. Previous studies (using observational and modeling approaches) have focused primarily on local climate effects on seasonal timescales, but shorter-term and non-local links have not previously been explored or identified. Here we present observational evidence and numerical modeling results to demonstrate a link between aerosols over the Arabian Sea and West Asia and Indian summer monsoon rainfall. Simulations using a state-of-the-art global climate model support this remote link and indicate that variability in dust aerosol loadings influence radiative heating rates that can induce larger scale circulation changes, modulating moisture transport and convergence over Central India, and change monsoon rainfall on relatively short time scales (about a week). Our simulations suggest that dust induced solar heating over North Africa and West Asia increases low-level winds over the Arabian Sea changing the moisture flowing into India. Our findings highlight the importance of natural aerosols in influencing the strength of the Indian summer monsoon, motivating additional research in how changes in background aerosols of natural origin may be influencing monsoon precipitation.

Key Words: Dust, sea-salt, natural aerosol, Indian monsoon, climate change
1. Introduction

The inter-annual variability of the Indian summer monsoon rainfall is only about 10% of the long term mean \(^1,2\); but these relatively small variations have important impacts on mankind and natural systems in India. A number of factors contribute to this variability, including aerosols that act directly (via solar radiation) and indirectly (through cloud microphysics) in influencing/modulating the monsoon strength. The role of aerosols in modulating monsoon rainfall over India has gained increased scientific attention in the recent past\(^3-12\).

Many recent studies have focused on anthropogenic and/or biomass burning aerosol influences\(^3,7,11-13\). However, the high winds over Arabian Sea associated with the monsoon not only act as a conduit for moisture from oceans, but also act as a source and conduit of natural aerosols of marine (sea-salt) and continental (dust, mobilized by Shamal winds over Arabia) origins that depend on both wind speed and direction\(^14-16\). These natural aerosols dominate the aerosol mass loading over the Arabian Sea and as we show below, likely influence the monsoon precipitation on short time scales.

Observational studies exploring pre-monsoon (April/May) aerosol loading and its effect on monsoon precipitation have found that maxima in aerosols lead precipitation\(^6,17-19\) by a month or more. There is observational evidence for an elevated heat pump\(^6\) (EHP) associated with a warming by dust and black carbon aerosol layers, that accumulates in the southern foothills of the Himalayas during the pre-monsoon period. The hypothesis is that this elevated heat source can advance the monsoon circulation and also strengthen rainfall during subsequent months, which has been a subject of scientific debate\(^18\). It has been challenging to obtain concomitant measurements of both aerosols
and precipitation at such large spatial scales (due to limitations in measurements and also their interactive nature) to explore aerosol/rainfall interactions \(^{20}\), and we know of no existing observational studies that have used concomitant aerosol and precipitation measurements on seasonal and shorter timescales. Aerosols can influence monsoons on multiple timescales: aerosol absorption and scattering can influence heating rates and stability in the atmospheric column and drive a relatively rapid monsoon response, but the reduction in sunlight reaching the surface can also affect the monsoon more slowly. The higher heat capacity of the surface leads to slower response in sea surface temperatures over the northern Indian Ocean producing a reduction of north-south temperature gradient with very important impacts on the monsoon\(^{11,21}\). Many climate modeling studies have focused on aerosol–monsoon precipitation interactions\(^{3-8,10,11}\); however, most of those concentrated on the slower forcing and response and the impact of changes in anthropogenic aerosol emissions. Only a few studies have focused specifically on natural aerosols \(^5\) or variations that occur on the faster sub-seasonal time scales.

In this paper we present evidence for the existence of a positive relationship between natural (mostly dust) aerosol and monsoon precipitation using temporally collocated but spatially separated satellite based aerosol and precipitation fields. The fields are correlated at short timescales (within a week). This observational relationship is also reproduced in simulations using an atmospheric global climate model (AGCM), which further suggest that dust aerosols over the North Africa, West Asia and Arabian region (operating through the fast forcing and response mechanism described above) modulate the summer monsoon precipitation over India.
2. Aerosol-Monsoon Precipitation Relationships

We analyze anomalies (relative to monthly means) of weekly precipitation over central India (averaged over 16.5-26.5°N, 74.5-86.6°E box shown in Fig. 1a selected to be similar to an All India Rainfall index used in reference 22) and weekly aerosol optical depth (AOD) at each grid cell over the domain covering the Indian sub-continent during the monsoon season (June to August). We use the global precipitation climatology project (GPCP) estimate for precipitation and AOD retrievals from the MODe rate resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) (more details on the observational data, model and methodology are provided in the supplementary materials). Figs. 1a and 1b show the correlation coefficient between Central India monsoon precipitation and AOD at each grid point over the Indian sub-continent based on satellite measurements (MODIS and MISR AODs). Fig. 1c shows the simulated relationship using the Community Atmosphere Model (CAM5) operating in “offline mode”, where the temperature, winds, and air mass (pressure) fields (called ‘meteorology’ hereafter) are prescribed by a reanalysis product23 (ERA Interim reanalysis for 2000-2009), and the aerosols and water variables evolve freely from the forcing provided by that meteorology (see supplementary material for details). In all three panels, the central Indian rainfall is strongly correlated with AOD over the Arabian Sea, West Asia and Saudi peninsular regions, but they have low or even negative correlations over the Eastern India and Bay of Bengal. A lead-lag analysis of weekly aerosols and precipitation variation indicates
that correlations are strongest (~0.6) for a zero-lag (Fig S3), indicating that aerosol and precipitation vary in concert.

It is important to understand the source of these correlations. Although there are clear relationships between pre-monsoon aerosol forcing, and monsoon precipitation, the lifetime of aerosols is very short (about a week) near the Earth’s surface, and the heavy precipitation during the monsoon effectively cleanses the atmosphere locally, so the mechanisms that connect aerosol and precipitation on longer seasonal time scales are probably not same as those evident on shorter timescales. In this study we focus on the shorter term aerosol/precipitation relations identified earlier, attempting to tease out the physical mechanism for the relationship, and the important aerosol types that contribute to it. Hints about the type of aerosols responsible for the observed relationship (shown in Fig. 1) are evident using the MODIS Angstrom Exponent (AE) product, an indicator of aerosol size (with lower values indicating dominance of larger sized particles). A similar pattern in AE of opposite sign (Fig. S2) suggests that coarse-mode particles dominated by sea-salt and/or dust are responsible for the positive correlations shown in Fig. 1. A similar analysis using a different MODIS product (i.e., fine-mode aerosol fraction) suggests no significant positive correlation between central-India precipitation and anthropogenic fine-mode aerosols over the Arabian Sea (as in Fig S2) and thus reinforces the above finding. It is difficult to discriminate between dust and sea-salt aerosol induced correlations using observations alone because both sources are sensitive to wind speed and contribute to the coarse size mode. We therefore resort to climate model simulations to separate the effects of different aerosols and expose the underlying physical mechanisms.
3. Model Results and Discussion

While models are imperfect, and may have difficulty in simulating all aspects of these correlations (especially on smaller spatial scales) they can provide significant insight into the working of the complex climate system. Various configurations of the CAM5 global climate model have been used (Table S1) to expose the physical mechanism behind the observed and modeled relationships seen in Fig. 1. The model includes treatments of the major aerosols species and their precursors, simulating dust, sea-salt, black and organic carbon, and sulfate. Aerosols affect the liquid and ice microphysics of stratiform clouds in the model (acting as nuclei for cloud liquid drop and ice crystal formation) and the radiative transfer calculation. As with most global climate models, aerosols do not directly affect the CAM5 convective cloud parameterization’s microphysics, but convection does respond to aerosol radiative forcing as it affects stability and the surface buoyancy fluxes. CAM5 can be run in “offline mode” as described earlier, or in its standard “free running” mode in which aerosols and meteorological fields evolve and interact simultaneously unconstrained by observations.

The correlation between central Indian monsoon precipitation and AOD for the free running CAM5 is shown in Fig. 2a. The spatial correlation pattern is similar to that seen in Fig. 1, but the positive correlation extends over a much larger area, covering the whole of Arabian Sea, Bay of Bengal and peninsular India. Modest changes to meteorology can have a large impact on the aerosol spatial distribution, but the model physical parameterizations (in both free running and offline mode) do reproduce the general correlation pattern, positive over Arabian Sea and negative over Northeast India.
(Areas where the free running and offline simulations produce different correlation patterns are regions where some caution is needed in inferring physical relationships from the free running simulations).

Additional simulations have also been made removing sea-salt, dust and anthropogenic aerosol sources individually, and in combination (see table S1 in supplementary materials for more details of the model experiments). Exclusion of these combinations of sources helps to determine the cause for the observed correlation patterns (Fig. 2). Note that natural pre-industrial (PI) emissions of OC and EC fire sources (wildfires), dimethyl sulfide (DMS) and background volcanic SO2 sources, and SOA emissions from vegetation were always included as aerosols sources.

A statistically significant relationship exists (with slightly changed spatial pattern) over the Arabian Sea with present-day (PD) anthropogenic aerosol sources when sea-salt and dust emissions are individually excluded (Fig. 2b and 2c). However, when both dust and sea-salt are removed (Fig. 2d), the amplitude of the correlation decreases and statistical significance disappears, indicating that both sea-salt and dust aerosols together contribute to the observed pattern. This also implies that anthropogenic aerosols alone are not responsible for the correlations, which is consistent with our interpretation of the AE, and fine/coarse mode partitioning of the aerosol retrievals (Fig. S2). Both dust and sea salt influence clouds and radiative heating. Removal of one species may have an impact on the other (through competition for water vapor, or vapor deposition of sulfuric acid and organics versus new particle formation etc27,28 and/or through changes to meteorology), affecting the precipitation downwind. Therefore, to identify the role of anthropogenic aerosols (within the model), we also repeated the analysis with pre-
industrial (PI) emissions. The observed patterns are very similar to those seen with PD anthropogenic emissions (Fig. 2a) when both dust and sea-salt natural emissions are included (not shown). This again implies that anthropogenic aerosols alone cannot produce these positive correlation patterns. However, as shown in the PI case (Figs. 3a &b), removal of any type of aerosol leads to a significant change in the observed correlation patterns. The most striking change is produced by the removal of the dust source (Fig. 3b), which leads to a complete disappearance and even change of sign in the observed correlations. Correlations are still present, but weaker when sea-salt sources are removed (Fig. 3a). The simulations suggest that the observed correlations can be reproduced only when dust is present along with either sea-salt or anthropogenic aerosols in the model. We note that in regions where aerosols are a minor player, and passively responding to meteorological variability, removal of one species ought not to strongly influence the correlation patterns. For example, removal of SO$_2$ emissions affecting the Arabian Sea does not strongly influence the correlation pattern there (not shown) and the central Indian precipitation response on these very short time scales.

The modeled summer monsoon rainfall response to changes in dust and sea-salt emissions is shown in Fig. 4. Sea-salt aerosol emissions lead to decreased precipitation over the coastal southern peninsular and central Indian region (Fig. 4a & c) and dust aerosol emissions lead to increased precipitation (Fig. 4b & d). Except for the intensity, the responses are identical in both the stratiform and convective precipitation. Since the convective precipitation microphysics is not linked to the presence of aerosols, the model precipitation response must be a function of local or remote circulation and stability changes (see next section), rather than a direct microphysical response (for example
through aerosol invigoration \(^{29}\). South of 15°N, over oceanic regions remote from India, the sea-salt correlates with increased rainfall, opposite behavior to that found over coastal and central India.

Although the timescale cannot be inferred from the time averaged response shown in Fig. 4, these seasonal changes in precipitation are consistent with the observed correlative signatures found with shorter weekly scales shown in Fig. 1; increased precipitation over central India is correlated with increased dust aerosols over Arabian Sea/West Asia and the Saudi peninsula. To elucidate the short time scale response of aerosol-precipitation interactions, another set of simulations called the Dust Pulse Experiment (DPE) was performed. Two sets of 10-day model simulations were made starting from initial conditions drawn during the monsoon period: one set of simulations included a dust source, while the other simulation set had no dust source, so dust concentrations dropped rapidly over the 10-day simulation period. All other aspects of the simulations were identical (see Fig. S10 and corresponding text for details). Changes in dust burden (over west Asia), and precipitation (over central India) were composited (by day of simulation) to identify the impact on precipitation as the dust is gradually scavenged (Fig. 5). The dust burden over West Asia/North Africa/Arabian region disappears quite rapidly, decreasing to 10% of its climatological regional average within 5-7 days. Average precipitation begins systematically decreasing over central India by day 7. The central Indian precipitation drops as dust concentration decrease in the west Asian region.
4. The physical mechanism behind the remote dust aerosols and Indian monsoon rainfall connection.

Dust is the largest contributor to the aerosol mass loading over northern Africa and West Asia including the Arabian Peninsula. Observational studies have shown that dust induced warming (clear sky) is the highest over Arabian Sea among the many dust laden regions\textsuperscript{30}. Our model estimates that dust aerosol increases top of the atmosphere (TOA) absorption of solar insolation (+6 Wm\(^{-2}\)), and decreases sunlight reaching the surface (-30 Wm\(^{-2}\)) producing a net atmospheric warming (+36Wm\(^{-2}\)) and surface cooling (dust aerosols can also change cloud microphysical properties, but this has a much smaller effect on model radiative forcing and circulation changes). This combined warming over regions with high dust concentrations leads to a reduction in surface pressure thereby driving large-scale convergence over the North Africa/Arabian Peninsula region (Fig. S7&8a). The climatological winds are mostly southwesterly over Indian region during the summer monsoon season. The convergent flow created by the dust heating over land regions to the north and west of Arabian Sea strengthens the northward component of the monsoon westerly (as a consequence of strengthening of the pressure gradient) over Arabian Sea (see Figs. 6, S7a, S8a & S9a) leading to increased moisture convergence (Fig. S9a) and precipitation (Fig. 4b) over the Indian region. This mechanism is consistent for both the observed seasonal relationships and the DPE and is summarized in Fig.S11 (see supplementary material for more information). The proposed mechanism operates as a result of remote dust aerosol forcing far from central India on a time scales of about a week, showing a different signature from the one the EHP hypothesis\textsuperscript{5} addresses.

We have used independent satellite retrievals to document a strong correlation between Arabian Sea AOD and central Indian monsoon precipitation occurring on short timescales. Satellite estimates of Angstrom Exponent and the Fine Mode Fraction (both characterizing particle size) suggest that the aerosol involved is either dust or sea salt. Our model shows a similar correlation, and our analysis indicates that desert dust aerosols (originating over North Africa / West Asia/Arabian region and appearing as high aerosol loading over the Arabian Sea) are responsible for the co-variability. This study suggests that the interaction operates as a “direct radiative effect” where the radiative heating near dust sources modulates the climatological monsoon westerly over the Arabian Sea with a resultant change in precipitation (~3 to 6%) over central India. This aerosol effect on precipitation through thermodynamics and large-scale circulation operates on timescales of less than a week, and it does not involve a change to sea surface temperatures (SSTs). While aerosols have been shown to be important in modulating sea surface temperatures, significant ocean temperature change is not expected on these very short timescales. The observed changes must primarily be a consequence of the atmospheric response to the aerosol induced radiative effect. Previous studies have shown that anthropogenic aerosols lead to decreases in Indian monsoon rainfall \cite{3,11,12}. These studies indicate that anthropogenic aerosols over India (or adjacent ocean regions) also act to affect local heating rates, and/or SSTs. We believe that the monsoon response to SST changes is very important (perhaps more important than the interaction we are documenting), but they operate on longer time scales. The present study shows that remote changes to natural
dust emissions as a consequence of anthropogenic and/or natural causes over regions to
the west of the Indian land mass, may also be modulating the rainfall over the Indian
region, highlighting the need to understand the effect of both natural and anthropogenic
aerosols and their interactions on precipitation in order to provide better predictions of
changes in monsoon precipitation.
6. Methods Summary

A weekly rainfall (using Global Precipitation Climatology Project daily dataset) time series (the region averaged over 16.5°N to 26.5°N and 74.5°E to 86.6°E) was created for the period 2000 to 2009 (June to August). This box was chosen as past studies have shown that the inter-annual variability of rainfall over this region is similar to that of all India rainfall (AIR) 22. The spatial and temporal homogeneity of rainfall, consistency with previous studies 3 and ultimately its relationship with all India rainfall were the important factors that influenced the choice of this box over India. The climatological monthly mean rainfall over this region was subtracted from each time point (corresponding to the month) to create a new time series of anomalies, forming the primary index of rainfall over central India for this study. Similar anomaly time series was created for the satellite-based AOD (MODIS and MISR) at each grid point over the Indian sub-continent region shown in Fig.1. The Correlation coefficient between the rainfall index over central India and the time series of aerosol optical depth at each grid point was calculated and shown in Fig.1 (a&b). The statistical significance was calculated using the standard student-\( t \) test. A dust pulse experiment was used to show the short time scale nature of the aerosol-monsoon link.
Figure Captions

Fig. 1: Correlation coefficient between precipitation (over central India as indicated by the box) and aerosol optical depth over the Indian region. (a) MODIS Terra (550 nm) and (b) MISR (558 nm) and (c) CAM5 in “offline mode” (550 nm). The black dots represent significance at 95% confidence level.

Fig. 2: Correlation between precipitation over central India and aerosol optical depth in free running simulations with present day emissions. Simulations include: (a) All species, (b) No Sea-salt, (c) No Dust and (d) No Sea-salt and dust for present day anthropogenic aerosol emissions. The black dots represent significance at 95% confidence level.

Fig. 3: Correlation between precipitation over central India and aerosol optical depth in free running simulations with pre-industrial emissions. Simulations include: (a) No Sea-salt and (b) No Dust for pre-industrial aerosol emissions. The black dots represent significance at 95% confidence level.

Fig. 4: The precipitation response associated with natural aerosol emissions (mm day\(^{-1}\)). The figure shows the control minus the simulation with suppressed dust or sea salt emissions) Left panels (a & c) indicate the role of sea-salt aerosols. Right panels (b & d) indicate the role of dust emissions. The top panels (a & b) show total precipitation (convective + stratiform precipitation) and bottom panels (c & d) only the stratiform precipitation. The black dots indicate a statistically significant change at the 95% confidence level.

Fig. 5: The short-time response of precipitation to dust forcing as estimated from the composite of two 19-member sets of 10-day simulations (the Dust Pulse
Experiment). The blue line corresponds to changes in precipitation over central India and red line shows dust burdens over West Asia when the dust emissions are disabled. The grey envelope represents the range of precipitation change between the 25th and 75th percentiles of the 19 member ensembles. The dotted red line shows the mean dust loading during the monsoon period from the control simulation.

Fig. 6: Schematic representation of circulation response (the aerosol induced anomalies) suggested in the paper from dust aerosols over West Asia/Arabian Sea. Land colors indicate altitude above mean sea level and vectors indicate the climatological direction of winds between June and August (from the NCEP Reanalysis). The darker elliptic region indicates the areas of increased warming from high dust concentrations that lead to a reduction in surface pressure that induces large-scale convergence over the North Africa/Arabian Peninsula region. The convergent flow created by the dust heating to the north and west of Arabian Sea strengthens the northward component of the monsoon westerly (brown arrows) as a consequence of strengthening of the pressure gradient over Arabian Sea. This leads to an increased moisture convergence and precipitation over the Indian region.
Fig. 1

(a) MODIS

(b) MISR

(c) CAM5-ERA
Fig. 3
Fig. 4
Fig. 6


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Supplementary Information is linked to the online version of the paper at www.nature.com/ngeo

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Author Contributions
VV and PJR primarily conceived the idea. VV carried out the data analysis and free running model simulations. PM and JHY carried out the offline and DPE model simulations respectively. All authors contributed through discussions and interpretation of the results. VV wrote a first draft of the paper with subsequent input from all the coauthors.

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Competing Interests The authors declare that they have no competing financial interests.