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Modulation of spatial distribution of aerosol species by the monsoon intraseasonal oscillation over South Asia

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Abstract

This study investigated the spatial and temporal modulation of aerosol species by monsoon intraseasonal oscillation (MISO) using the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations from 2003 to 2019. The climatological spatial distribution of aerosol species showed long-range transport of sea-salt and dust to Indian landmass from the Arabian Sea and desert regions of the Arabian Peninsula, respectively. While organic matter, black carbon, and sulfate originated mainly in India. In the eight MISO phases, southwesterly/westerly strengthening/weakening was responsible for aerosol species transport and spatial distribution. During MISO break to active transition phases 2–5, strong southwest monsoon winds transported sea-salt aerosols from the Arabian Sea to the Indian region. In the active-to-break transition phases 5–7, dust transport strengthened from the Arabian Peninsula. The dust aerosols over the Indian subcontinent peaked in phases 6 and 7. In phases 2–5 (6–8, 1), direction of strong winds along the Indo-Gangetic Plain influenced increased levels of organic matter, sulfate, and black carbon aerosols in the western/northwestern (eastern/northeastern) regions of India. These dynamic spatial changes in aerosols caused by MISO over the Indian region influence the shortwave and longwave radiation balances that can influence monsoon circulation.
1. Introduction

In the past two decades, tremendous progress has been made in understanding monsoon intraseasonal oscillation (MISO), which has helped improve the prediction skill of climate and forecasting models. MISO plays an important role in distribution of summer monsoon precipitation, causing wet/dry periods in India (Suhas et al. 2013; Li et al. 2018). However, their interaction with aerosols may modulate precipitation characteristics. Therefore, a better understanding of aerosols, which influence regional and global climates, is essential for improving the prediction skill of climate models.

Satheesh and Ramanathan (2000) reported direct and indirect effects of aerosols on climate. The direct effects of aerosols include scattering, absorption, and reflection of incoming solar radiation (Lohmann and Feichter 2005). Indirectly, aerosols modify the microphysical properties, albedo, and lifetime of clouds (Bollasina et al. 2011). Through these direct and indirect effects, aerosols may influence the climatological features of the Indian summer monsoon season.

To understand how aerosols interact with summer monsoon activity and rainfall over India, it is important to understand their composition, relative contribution, and dynamics over the Indian subcontinent. In the study by Li et al. (2016), it is stated that aerosols are transported by winds related to weather patterns, which allow the aerosols to move across space-time and distribute. In line with their study, we investigated the role of summer monsoon winds in transporting aerosols over the Indian region. We considered changes in lower atmospheric summer monsoon wind patterns by MISO and investigated their influence on aerosol transport from the location of sources of different species.
2. Datasets and Methodology

2.1 Datasets

To analyze the aerosol species in each MISO phase, we used the Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis dataset (Innes et al. 2019) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). This dataset is the latest reanalysis dataset on atmospheric composition and is available at a temporal resolution of 3 h and spatial resolution of 0.75° × 0.75° from 2003–2019. This dataset was used to analyze the total aerosols, which is primarily the sum of dust, sea-salt, organic matter, sulfate, and black carbon aerosols in each MISO phase. Furthermore, we compared the spatial distribution of total aerosols from the reanalysis dataset to observations at 550 µm. For the observations, we used daily Moderate Resolution Imaging Spectroradiometer (MODIS) datasets from the TERRA and AQUA satellites (Savtchenko et al. 2004) for the same period (2003–2019) at a spatial resolution of 1° × 1° at 550 µm. We used the radiation flux datasets of Clouds and the Earth’s Radiant Energy System (Doelling et al. 2016). Daily rainfall datasets were considered from the Integrated Multi-satellite Retrievals for GPM datasets (Huffman et al. 2015).

The winds at a lower level (850 hPa) in the summer monsoon season June–September (JJAS) were analyzed using the hourly ECMWF reanalysis, version 5 (ERA5; Hersbach et al. 2020) dataset for the same period (2003–2019). This is the fifth-generation reanalysis dataset and was prepared at a 30-km resolution by the Copernicus Climate Change Service at the ECMWF.

2.2 Methodology

Monsoon intraseasonal variability was investigated using the MISO index (Suhas et al. 2013). This index provides excellent real-time monitoring of low-frequency (25–90 days) MISO. This index provides the dates of the eight MISO phases during the summer monsoon season. The data
for this index computed for 1998–2019 can be downloaded from the Indian Institute of Tropical Meteorology website (https://www.tropmet.res.in/erpas/files/miso_data.php). Each MISO phase has different features, depending on the position of the monsoon trough, which we will discuss in more detail in section 3.2. The significance of the spatial distribution of anomalous aerosols and absolute winds was analyzed using the t-test at a significance level of 0.05. The relative change of area average mean aerosol species during each MISO phase was computed with respect to all MISO phases.

3. Results

3.1 Climatology of aerosol species

To identify the regions where aerosol species were dominant, we analyzed the climatology of aerosol species during the summer monsoon season from 2003–2019. The aerosol optical depth (AOD) of total aerosols over India showed spatial variation (Fig. 1a); it was higher in northern and northeastern India and lower in the southern peninsular region. This spatial distribution of total aerosols appeared in both the observation and reanalysis datasets (Fig. 1a; Supplementary Fig. 1). The climatological features of aerosols can be further described for aerosol species such as sea-salt, dust, black carbon, organic matter, and sulfate.

According to the climatology, the Arabian Sea has more sea-salt aerosols than the Bay of Bengal, and other nearby land regions have fewer sea-salt aerosols (Fig. 1b). There are more dust aerosols in three nearby areas of the Indian subcontinent, where deserts prevail: the Thar Desert, Arabian Peninsula, and northern Tibetan Plateau (Fig. 1c). The black carbon aerosols were more in the Indo-Gangetic Plain and the Arabian Peninsula (Fig. 1d). This may result from the consumption of fossil fuels in these regions. Organic matter and sulfate aerosols were dominant in the Indo-Gangetic Plain and in the southern part of the Arabian Peninsula, possibly due to biomass
burning (Figs. 1e, f). These climatological features of aerosols AOD explain the possible dominant (source) regions of aerosol species over different subregions of India. Interestingly, we can observe some amount of aerosols distributed across space pointing to their transport from the dominant regions.

Each aerosol species contribution (%) to the total aerosol was analyzed in different sub-regions. Aerosol species contribution shows large spatial variations. The contributions of these aerosol species to the total aerosols were quantified. In western and northern India, dust aerosols were responsible for a large contribution of 40–50%, sea-salt contributed 15–20%, and organic matter and sulfate contributed 25–35%. Black carbon was responsible for the smallest contribution (less than 5%) in these regions. In northeastern India, the contributions of dust, sea-salt, sulfate, organic matter, and black carbon aerosols were approximately 10–20%, less than 10%, 40–50%, 50–60%, and 5%, respectively. In contrast, in southern India, the contributions of dust, sea-salt, sulfate, organic matter, and black carbon aerosols were approximately 20%, less than 20%, 25%, 25%, and less than 5%, respectively. Thus, aerosol species make different contributions to the total aerosols in different provinces of India. These differences in the contributions of aerosol species modulate meteorological parameters, such as rainfall, clouds, and radiation budget, differently in various Indian subregions.

3.2 Relationship between distribution of aerosols and MISO

To understand the role of monsoon winds in the distribution and transportation of aerosols over the Indian landmass, it is important to understand the wind patterns in each MISO phase. Because the aerosol species of focus are at the surface, lower atmospheric winds are important for transporting the aerosols. Figure 2 shows the absolute winds at 850 hPa and anomalous total AOD in each MISO phase computed using the ERA5 and CAMS reanalysis datasets, respectively. The
Variations in AOD computed using the reanalysis dataset were similar to those of the MODIS observations (Supplementary Figs. 2a–h).

Strong southwesterly winds in the summer monsoon season varied in mean magnitude, position, and state, depending on the MISO phase (Supplementary Figs. 3a–h). Monsoon winds (westerlies/southwesterlies) over the ocean travelled northeastward/northward and strengthened as MISO progressed (phases 1–5; Figs. 2a–e). As these winds moved northward with the MISO progression, anomalous aerosols also propagated northeastward/northward. In addition, the aerosol concentration increased when these winds crossed the eastern part of North Africa and the Arabian Peninsula (Figs. 2b–e); thus, aerosol transport to the Indian landmass began to increase.

In phases 6–7 (Figs. 2f, g), the southwesterly winds on the Arabian Sea weakened, and the northwesterly winds (westerly) in northern India (the Arabian Sea) became stronger. These winds distributed a large amount of aerosols from the Thar Desert and Arabian Peninsula. Consequently, the total aerosol concentration in India reached their peak amount. Thereafter, in northern/northwestern India, the Arabian Sea, and the Arabian Peninsula, aerosol concentration decreased in phase 8 (Fig. 2h), and anomalous aerosol loading occurred over the eastern region of India and along the northeastern flank of the Indo-Gangetic Plain. In addition, aerosol transport by monsoon winds over India was reduced. Here, the strengthening and weakening of monsoon winds during the MISO phases effectively represent loading and unloading of aerosols over the Indian land mass.

### 3.3 Meridional movement of aerosol species

The spatial distribution of aerosols and their movement over the Indian longitudes (70°–85° E) revealed interesting features in the latitudinal variation of aerosol species (Fig. 3). Sea-salt from the Arabian Sea was transported to the Indian region by strong southwesterly winds in phases 1–
5. As the monsoon winds propagated northward, they traveled from southern to central India (Fig. 3b). This sea-salt transport weakened when wind over the Arabian Sea became somewhat weaker. Northern India generally has more dust aerosols because of the presence of the Thar Desert (Fig. 3c). Latitudinal variation in dust aerosols also occurs because of monsoon winds. The amount of dust aerosols over the central and southern parts of India (10°–20°N) was higher during phases 4–7, and lower amounts were seen in phases 1–2 and 8. While for the northern parts of India (24°–30°N), the dust aerosols were higher in phases 1 and 5–8 and lower in phases 2–4. Therefore, meridional transport of dust to the Indian region occurred during the various MISO phases in different parts of India.

Black carbon, organic matter, and sulfate aerosols were more in the Indo-Gangetic Plain (Figs. 1d–f and 3d–f). We observed southward transport of these aerosol species from the Indo-Gangetic Plain to central and southern peninsular regions of India in phases 3–7. During the other MISO phases, this southward transport decreased. Not all aerosol species exhibited the same meridional movement during each MISO phase. To better understand the reasons for these differences in meridional variation, we analyzed the effect of wind on each aerosol species separately.

### 3.4 Movement of aerosol species by MISO winds

We found that the climatological peaks of aerosol species were associated with aerosol transport from their regions of origin to different parts of the Indian land during certain MISO phases. The significant anomalous spatial distribution and transport of sea-salt, dust, and organic matter aerosols were analyzed with significant lower atmospheric monsoon winds (Figs. 4, 5, and 6, respectively). The spatial distributions of sulfate and black carbon aerosols with significant lower atmospheric winds, which are similar to those of organic aerosols, are shown in Supplementary Figs. 3 and 4, respectively.
The winds in MISO were strongest over the Arabian Sea in phases 2–4 (Supplementary Fig. 2). These strong winds transported a significant large amount of sea salt from the Arabian Sea to southern India (Fig. 4). In addition, sea-salt moved meridionally as the monsoon winds moved across the Indian land mass (phases 5–7), but at lower concentrations. Thus, increased sea-salt over the Indian landmass occurred in phases 2–4, in which the southwesterly winds in the Arabian Sea were the strongest.

Strong southwesterly monsoon winds over the Indian landmass carried dust aerosols from the Arabian Peninsula and eastern Africa (Fig. 5). The amount of dust aerosols in the monsoon winds increased when there were more dust aerosols over the Arabian Peninsula (phases 4–7). These dust aerosols were transported by westerly/northwesterly monsoon winds from the Arabian Peninsula to the Indian landmass. In phases 4–5, strong monsoon winds carried very large amounts of dust over southern and western India. In contrast, in phases 6–7, southwesterly/westerly winds with very large amounts of dust aerosols entered northern India and shifted northwesterly, transporting the aerosols from northern India to the southern peninsular regions. Thus, over India, dust aerosols were transported/loaded through long-range transport by strong southwesterlies/westerlies when dust concentration over the Arabian Peninsula was high (phases 4–6).

Remarkably, some organic aerosols in southern India arrived through long-range transport from the African continent or Arabian Peninsula in phases 4–6 (Fig. 6). However, most of these aerosols were transported from the Indo-Gangetic Plain according to the direction of winds (Supplementary Fig. 3). Similarly, black carbon and sulfate aerosols also arrived through long-range transport in phases 4–6 (Supplementary Figs. 4 and 5). In other MISO phases, they originated from a region of high concentration in northeastern India.
4. Discussion

Using the variations in monsoon lower atmospheric winds due to MISO, we examined the modulation of aerosol transport and spatial distribution. MISO also modulated the spatial patterns of aerosol species by transporting them via lower atmospheric winds from their region of origin to other areas where the aerosol species did not originate. Among the five aerosol species, dust, organic matter, and sulfate were present in greater amounts than sea-salt and black carbon in central India (Fig. 7a). The relative change in aerosol species during MISO phases can quantify the MISO modulation of aerosols. The relative changes in the long-range transport of dust and sea salt aerosols were approximately 50% and 40%, respectively (Fig. 7b). For the other aerosols, this varied from 5% to 10% during the different MISO phases.

The relative change in aerosols during MISO can have both direct and indirect effects on the atmosphere, which could influence changes in radiative fluxes and cloud properties (Francis et al. 2021), respectively. For example, Sarangi et al. (2018) revealed that the net cooling of the lower atmosphere during the Indian summer monsoon season is due to the presence of aerosols and clouds. Similar instances of cooling of the lower atmosphere can be seen in the present study during MISO phases 5–7, where the amount of aerosols and cloud fractions were relatively higher than during other phases (Fig. 7c). Enhanced aerosols, along with cloud fractions, can reduce the incoming shortwave radiation to the surface and increase the amount of outgoing longwave radiation at the top of atmosphere (Fig. 7c; Twomey et al. 1984; Ramanathan et al. 2001; Rosenfeld et al. 2008). Such a reduction in incoming solar radiation during MISO phases 5–7 due to aerosols and/or clouds may influence the atmospheric state by increasing the stability in the lower atmosphere, could potentially suppress monsoon convection over the region. Ramanathan et al.
(2001) and Prasad and Singh (2007) examined similar type of suppression of monsoon convection owing to the radiative effect of aerosols during summer monsoon season.

Another aspect of aerosol interactions is aerosol-clouds indirect effect (Sarangi et al. 2017), where the presence of aerosols could increase the cloud development over the Indian monsoon region. However, analyzing the cloud properties and indirect effects of aerosols is beyond the scope of the current study. Moreover, it is difficult to understand the dominant type of aerosol interaction during MISO phases. Further investigation is needed to understand the direct and indirect effects of aerosols during MISO phases.

Moreover, owing to the limitations of the CAMS dataset, we were not able to compute the contribution of individual aerosol species to radiative forcing, which may be possible if radiation absorption is available for individual aerosol species. However, based on the contribution and relative change in aerosol species during the MISO phases (Fig. 7b), we can relate their possible role in contributing to radiative changes (e.g., Ramachandran et al. 2020; Jangid et al. 2021). Therefore, the combined effects were analyzed in this study. The individual roles of aerosol species and their direct and indirect effects require further investigation.

5. Summary

This study found that the climatological variability in monsoon winds during the MISO influenced the spatial distribution of aerosol species. The wind direction and strength in the Indian region differed in each of the eight MISO phases. These differences influenced the spatial distribution of the aerosol species. In combination, the wind patterns and dominant regions of different aerosol species contribute to our understanding of their geographic distribution. The possible region of origin of aerosol species can be identified using the mean spatial distribution of aerosols. For example, sea-salt and dust aerosols are found mainly over the Arabian Sea and desert
regions of the Arabian Peninsula, respectively. Black carbon, organic, and sulfate aerosols appear to be more common in the Indo-Gangetic Plain and parts of the Arabian Peninsula. Aerosol species were transported from these origin regions to different parts of the Indian landmass during the MISO phases.

An interesting aspect of this study is the modulation of the spatial distribution of aerosol species in different MISO phases with lower atmospheric winds, which provides information regarding their dynamics. These dynamic changes in aerosol species were associated with changes in wind patterns due to the MISO during the summer monsoon season. Such MISO-driven spatial variations in aerosol species influence local convection, which may influence the temporal and spatial distributions of summer monsoon precipitation. This type of study can provide important information on the effects of aerosol species on local dynamics, incoming/outgoing solar radiation, and cloud properties based on changes in aerosol spatial distributions.
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Supplements

Supplement 1: Additional figures (S1–S5) related to the analysis are included in the Supplementary Information.
List of Figure Captions

Fig. 1 Climatology (2003–2019) of mean aerosol optical depth (AOD) at 550 µm of a) total aerosols, b) sea-salt, c) dust, d) black carbon, e) organic matter, and f) sulfate aerosols using the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis dataset for June–September.

Fig. 2 Significant mean 850 hPa winds (vectors) and total AOD anomalies (background color) in eight phases of monsoon intraseasonal oscillation (MISO) (a–h). Winds and total AOD were obtained from the European Centre for Medium-Range Weather Forecasts, version 5 (ERA5) and CAMS reanalysis datasets, respectively. Reference magnitude of wind vectors is 15 m s⁻¹. Green dots represent the anomalous total aerosol at a significance level of 0.05.

Fig. 3 Monsoon intraseasonal latitudinal variation in aerosol components based on the CAMS dataset. Analysis based on a 17-year mean (2003–2019). The horizontal axis shows MISO phases (P1–P8), and the vertical axis shows latitude. Longitudinal average is considered across 70°E–85°E.

Fig. 4 Significant absolute winds (vectors) and sea-salt AOD anomalies in each MISO phase (background color). Winds and sea-salt AOD are from the ERA5 and CAMS reanalysis datasets, respectively. Reference magnitude of wind vectors is 15 m s⁻¹. Green dots represent the anomalous sea-salt AOD at a significance level of 0.05.

Fig. 5 Similar to Fig. 4, but for anomalous dust aerosols.
Fig. 6 Similar to Fig. 4, but for anomalous organic aerosols.

Fig. 7  a) Absolute change and b) relative change in AOD of total aerosols and aerosol species during eight MISO phases (P1–P8). c) Relationship between total aerosols, shortwave and longwave radiation fluxes (W m⁻²), cloud fraction, and rainfall in eight MISO phases. Total aerosols, solar radiation fluxes, cloud fraction, and rainfall are from CAMS reanalysis, Clouds and the Earth’s Radiant Energy System (CERES) observations, CERES observations, and Integrated Multi-satellite Retrievals for GPM (IMERG) observations, respectively, averaged over central India (15°N–25°N; 70°E–85°E).


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Fig. 1 Climatology (2003–2019) of mean aerosol optical depth (AOD) at 550 µm of a) total aerosols, b) sea-salt, c) dust, d) black carbon, e) organic matter, and f) sulfate aerosols using the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis dataset for June–September.
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Fig. 7  a) Absolute change and b) relative change in AOD of total aerosols and aerosol species during eight MISO phases (P1–P8).  c) Relationship between total aerosols, shortwave and longwave radiation fluxes (W m$^{-2}$), cloud fraction, and rainfall in eight MISO phases. Total aerosols, solar radiation fluxes, cloud fraction, and rainfall are from CAMS reanalysis, Clouds and the Earth’s Radiant Energy System (CERES) observations, CERES observations, and Integrated Multi-satellitE Retrievals for GPM (IMERG) observations, respectively, averaged over central India (15ºN–25ºN; 70ºE–85ºE).
Supporting documents for
Modulation of spatial distribution of aerosol species by the monsoon intraseasonal oscillation over South Asia

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**Fig. S3** Mean absolute winds at 850 hPa in eight phases (a–h) of MISO using ERA5 reanalysis dataset. Colored background shows winds speed and vector represents winds direction. Reference magnitude of the wind vector is 15 m s\(^{-1}\).
Fig. S4 Significant absolute winds (vectors) and black carbon AOD (background color) shown during the eight MISO phases. Winds and black carbon AOD were obtained from the ERA5 and CAMS reanalysis datasets, respectively. Reference magnitude of the wind vector is 15 m s\(^{-1}\). Green dot represents the anomalous black carbon AOD at a significance level of 0.05.
Fig. S5 Similar to Fig. S4, but for anomalous sulfate aerosols.