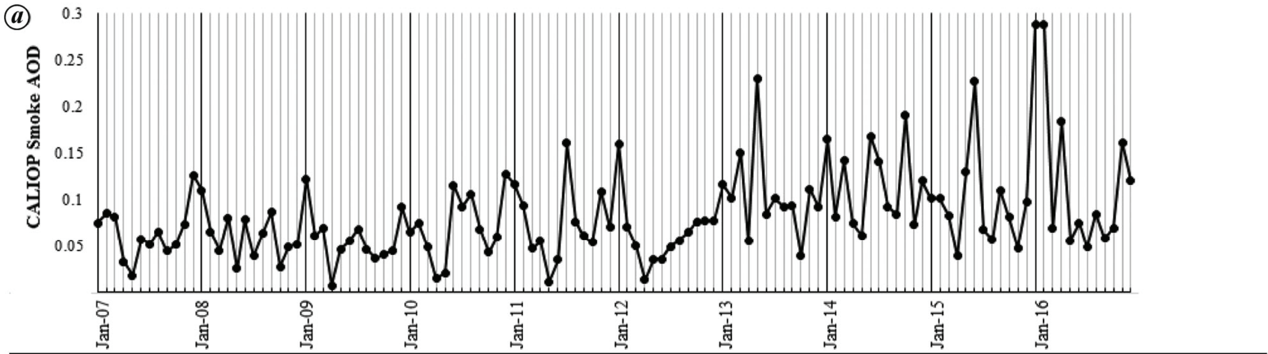
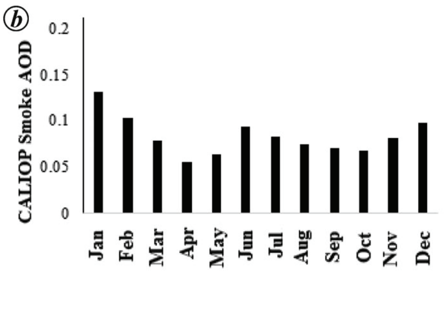
Increasing smoke and carbonaceous aerosols over the Indian region (2007–2016)

Aerosol particles in the Earth's atmosphere are known to have serious climatic and health implications. The smaller particles like smoke aerosols (SAs) can easily enter into the human body and have harmful impacts. A previous study has shown that black carbon (BC) may act as a carrier of chemical constituents of variable toxicity and adversely impact the lungs and blood circulation[1]. These suspended smoke particles in the atmosphere can also affect the Earth's radiation budget[2]. The overall radiative forcing effects from smoke emissions depend on the nature of the source of these emissions. The Indian region, one of the major aerosol hotspots, is known to have SAs of both natural and anthropogenic origin. Smoke emissions are major contributors to the primary carbonaceous aerosols (CAs) in the atmosphere. A previous study has revealed that around 80% of CA emissions from the Indian region originate from anthropogenic activities, mostly for meeting the energy requirements[3]. Some previous works have reported the aerosol trends using passive sensors[4–6], but they were mainly focused on providing the overall trends in aerosol optical depth (AOD) over the Indian region, rather than trends specific to a particular aerosol type. Further, there have been some studies focusing on variability of SA/CA over the Indian region; however, most of them are limited to a regional scale[7,8]. A recent study has discussed the variability of different aerosol types but not their trends[9].

In this study, decadal-scale trends (2007–2016) for SAs have been reported by the analysis of datasets from Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), on-board Cloud–Aerosol Lidar and Infrared Path-finder Satellite Observations (CALIPSO)[10]. The Level-3 monthly datasets, CAL_LID_L3_APro_AllSky-Standard-V3-00, utilized in this study have been generated using quality checks and screening of Level-2 data products[10,11]. These global products provide AOD and extinction profiles of the major aerosol types at a spatial resolution of 2° × 5° and a vertical resolution of 60 m up to 12 km amsl (ref. 12). Also to be noted is that only the night-time data have been used as the daytime CALIOP data are more noisy. The vertical profiles were averaged within three altitude bins, i.e. 0–2, 2–4 and 4–6 km amsl. For comparative purpose, the monthly AOD data due to CAs (black/organic carbon) carbonaceous aerosol optical depth (CAOD) were obtained from Level-4 Modern-Era Retrospective Analysis for Research and Application-2 (MERRA-2) reanalysis products[13]. The datasets are available at a spatial resolution of 0.5° × 0.625°. Readers may refer to previous works on the evaluation of MERRA-2 products with respect to satellite and *in situ* observations[13,14].

Figure 1 *a* shows the decadal variability of smoke aerosol optical depth. It can be clearly seen that during the second half of the decadal period, smoke particles have increased in the atmospheric column. Figure 1 *b* presents the monthly variation of smoke loading during the considered time-period. We can observe high smoke loading during November–February associated with biomass burning activities as well as high smoke during May–July associated mainly with forest fires. Figure 1 *c* presents the SE





c

SE (%) within different altitudes (amsl)

	0-2 km	2-4 km	4-6 km
JANUARY	61.83	36.76	1.41
FEBRUARY	48.87	48.59	2.55
MARCH	38.76	50.72	10.52
APRIL	32.7	54.91	12.39
MAY	39.97	48.37	11.66
JUNE	38.22	51.92	9.86
JULY	45.19	45.79	9.01
AUGUST	53.21	38.52	8.28
SEPTEMBER	55.34	35.94	8.72
OCTOBER	55.26	40.07	4.67
NOVEMBER	64.25	30.24	5.51
DECEMBER	67.5	30.58	1.92

Figure 1. ***a***, Decadal variation of smoke aerosol optical depth (SAOD) from CALIOP. ***b***, Ten-year monthly variability in SAOD. ***c***, SE (%) within different altitude bins.

Table 1. Decadal trends of smoke aerosol optical depth (SAOD) (from CALIOP) and carboneous optical depth (CAOD) (from MERRA-2 reanalysis) (statistically significant trends are represented in bold)

	Trends	
	SA	CA
January	**Increasing**	Increasing
February	**Increasing**	**Increasing**
March	–	Increasing
April	**Increasing**	Increasing
May	**Increasing**	**Increasing**
June	**Increasing**	–
July	Increasing	–
August	Increasing	Decreasing
September	**Increasing**	**Increasing**
October	**Increasing**	–
November	**Increasing**	**Increasing**
December	Increasing	–

(%) observed in three altitude bins. One can observe that generally, majority of the SA load is found within 0–2 km during August–January. However, during March–June, considerable amount of SA stays within higher altitudes (2–4 km). These findings are in agreement with those of previous studies utilizing satellite/*in situ* measurements, where smoke has been noted at elevated altitude levels[15,16]. This can be further understood in terms of planetary boundary layer height (PBLH) over the Indian mainland that bears a distinct seasonality with a generally higher PBLH during March–June over majority of the places, compared to other months of the year. In this context, it has been observed from radiosonde measurements and MERRA reanalysis datasets that the boundary layers are the deepest during pre-monsoon over the Indian region[17]. This higher PBLH could be associated with higher near-surface wind speeds, higher surface temperatures and uplifting of particles. Further, linear regression technique was used to estimate the decadal trends in SAs (and CAs). It is clear from Table 1 that the SA load has increased over the decadal time-period under consideration. The enhancement of these particles during October–February (when the atmospheric conditions are more stable relative to other months of the year) could be a clear indication of increase in anthropogenic activities over the Indian region during this period. Increasing trends in CAOD have also been found in February, May, September and November. To this end, a recent study has also reported an increase of about 20% in the fire counts over Central India using satellite and model reanalysis datasets spanning over 15 years[18]. In yet another study, increasing trends of vegetation fires have been observed over India (2003–2016)[19]. On the other hand, increasing trends of smoke during the dust-dominated periods of summer are alarming with increasing rates of forest fire and surface temperature in the country[20]. There are reports of growing mid-monsoon dry phases over the Indian region[21]. This increase in dry phases can be further seen in conjugation with declining monsoonal precipitation and increasing anthropogenic activities[22].

This study presents a space-based view of increasing SAs in a decadal period over the Indian region. Though the model reanalysis outputs are also presented, a focused study involving evaluation of long-range transport models and emission inventories can provide complete information on the changing smoke/carbonaceous load, which can be of particular concern to policymakers in the changing climatic scenario.

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