A satellite view of the changes in summer-time aerosol vertical distribution before and during COVID-19 lockdown conditions in India

Aerosols are known to have direct and indirect effects on the Earth's climate system[1]. It is not only the knowledge of the total atmospheric aerosol load that is of concern, but also important is the dynamics of the aerosol distribution across different vertical sections of the atmosphere. The Indian region experiences a heavy aerosol loading during the pre-monsoon season[2], accompanied with high air temperature. Specifically, the Indo-Gangetic Plains (IGP) witness higher aerosol load compared to the rest of the country owing to the prevailing meteorological conditions apart from anthropogenic activities[3]. Due to the lockdown imposed during COVID-19 in the entire country, a decrease in the aerosol loading and gaseous emissions has been observed and reported over several regions using ground-based measurements[4–6]. Here, we highlight the changing aspects of the vertical distribution of aerosols before (2015–19) and during the lockdown period (2020) for April–May, as observed by Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), on-board the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission[7]. These observations are supported by the measurements on columnar aerosol loading as seen from different sensors, as well model reanalysis datasets.

The results are presented in terms of two parameters, one representative of vertical distribution of aerosols, i.e. extinction coefficient (expressed in km^{-1}) and the other for column integrated values, aerosol optical depth (AOD, dimensionless). The extinction coefficient is indicative of the light extinct by the aerosols due to absorption or scattering and is a function of the altitude above the surface of the Earth. Further, integrating the extinction coefficients over the length of the atmospheric column yields AOD. Higher the aerosol amount, higher will be the extinction coefficient and so would be the overall AOD. Figure 1 *a* presents the 5-yr averaged AOD variability during April–May 2015–19 compared with that of 2020 over the Indian region using data from Moderate Resolution Imaging Spectroradiometer (MODIS) on-board NASA's AQUA (Level 3 AOD at 550 nm), Ozone Monitoring Instrument (OMI) onboard NASA's AURA (Level 3 AOD at 500 nm), MERRA-2 Model Reanalysis (AOD at 550 nm), as well as from CALIOP on-board the joint NASA and CNES's CALIPSO mission (Level 3 extinction profiles and AOD at 532 nm). For instrumental/observational/retrieval/uncertainty details, one may refer to the previously published works[7–10]. It can be further noted that the spatial extent of the study area lies within the range 8°4′–37°6′N and 68°7′–97°3′E. Systematic difference/bias in the AOD values from CALIPSO with respect to that from other datasets could be a function of different aerosol types over different locations apart from differences in retrieval approaches, as illustrated in a previous study[11] and references therein. One can easily observe the overall reduction in the AOD values during lockdown over different regions of India from Figure 1 *b* in particular, over the IGP (Figure 1 *c*). We also observe a systematic pattern of no significant changes and/or increase in the mean AOD during lockdown at certain locations like northern Kerala, Karnataka, Telangana, Andhra Pradesh, Odisha and West Bengal. The exact reason for this requires detailed analysis of different aerosol sources, long-range transport and meteorological

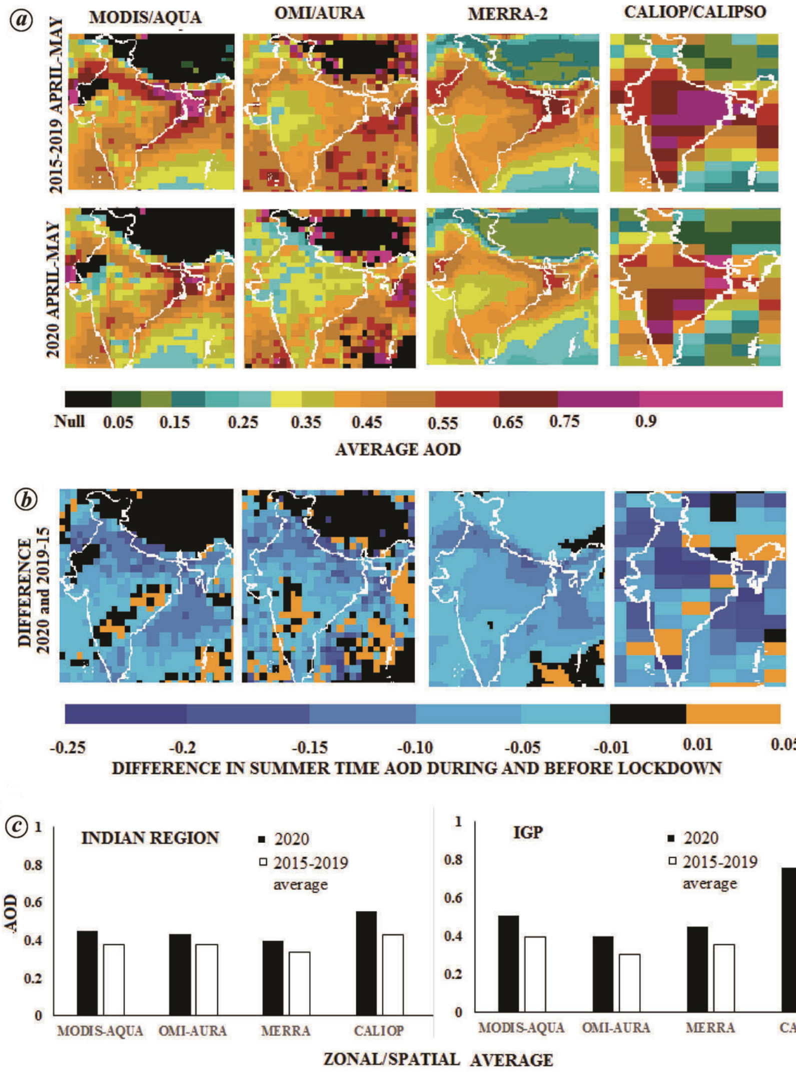

Figure 1. ***a***, Spatial AOD variability over India. ***b***, AOD difference (2020–(2015–19 averaged)) over India. ***c***, Zonal averaged AOD values over the Indian region and Indo-Gangetic Plain; results presented for April–May (2015–19 and 2020).

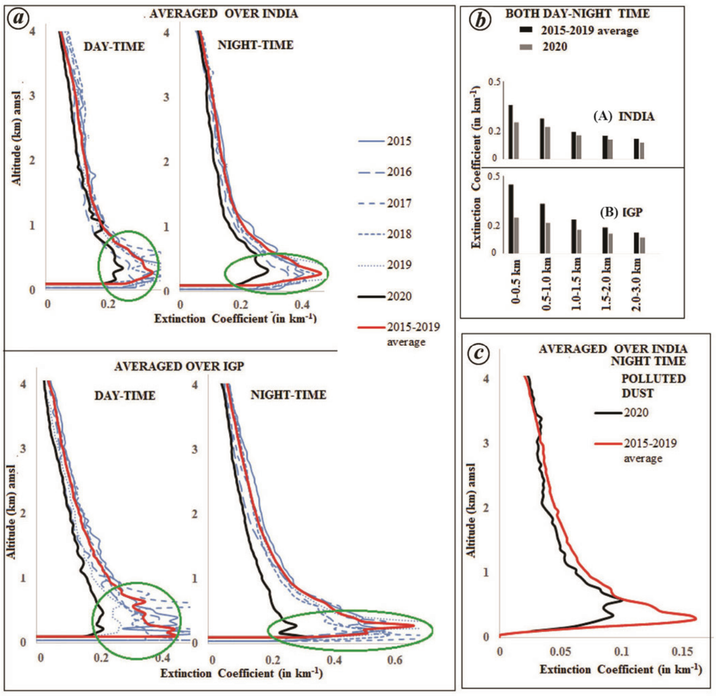

Figure 2. ***a***, Daytime and night-time aerosol vertical distribution. ***b***, Day–night averaged distribution of aerosols within different altitude bins over (A) India and (B) IGP. ***c***, Vertical distribution of night-time polluted dust over India; results presented for April–May (2015–19 and 2020).

conditions. In this context, a recent study has reported 'no significant reduction' in aerosol amounts during lockdown over the regions dominated by coal mining activities (in order to meet the energy requirements)[12]. Another study reported increased smoke from active fires at some locations during the initial lockdown phase[13]. Figure 2 *a* shows the changes in the vertical distribution of aerosols over the Indian region and over IGP as a special case. We can observe that during the daytime, the aerosols in the boundary layer are more vertically mixed compared to the night-time where they are confined closer to the surface. This can be better understood in terms of diurnal changes in the convectional factors and the atmospheric boundary layer height. Considering the daytime and night-time averaged aerosol profiles, a reduction of around ~30% in the aerosol extinction values has been observed over the entire Indian region near the surface (~500 m). Of particular interest is the near-surface change in the aerosol vertical distribution over IGP, where we can observe a larger reduction (~45%) in the aerosol extinction. For a quantitative understanding, we have presented the mean extinction coefficient values of aerosols within five altitude bins, i.e. 0–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0 and 2.0–3.0 km, wherein maximum aerosol extinction is observed in the bin closest to the surface (Figure 2 *b*). It can be noted that in addition to the natural desert dust, a major aerosol type in pre-monsoons, polluted dust (which is a mixture of dust and smoke or urban pollution) is also dominant over several parts of the Indian region[14]. Hence apart from the changes in natural aerosols, a decline in anthropogenic activities can be observed in terms of changes in vertical profiles of polluted dust, as illustrated in Figure 2 *c* over the Indian region (night-time).

The COVID-19 lockdown condition has presented before us a classic example of the impact of reduction in anthropogenic activities on air quality as well as the vertical aerosol distribution, even over the areas that otherwise experience high natural aerosol loading (dust) during the pre-monsoonal phase. The information on changes in vertical distribution of aerosols in pre- and post-lockdown conditions in conjugation with the knowledge on vertical distribution of meteorological parameters like temperature, wind, humidity, etc. can provide useful inputs to the researchers and policymakers working in the domain of climate change mitigation. A detailed analysis will also require comparison with the data from ground-based measurements (lidars) deployed across the study area, which can be taken up as future study.

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