Changing Trends of Aerosol Loadings Over Three Major Zones of Indian Region During the Last Seventeen Years (2005–2021)

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Abstract
The spatial and temporal variation of satellite derived pre-monsoonal Aerosol Optical Depth (AOD) over the Indian region has been studied using long-term (2005–2021) satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS) and Ozone Monitoring Instrument (OMI). In particular, three zones were selected, based on the dominance of natural, anthropogenic and mixture of both types of aerosols. The seasonal average of AOD (MODIS, OMI) was found to be (≈ 0.40, ≈ 0.35) for the entire Indian landmass. We found that the trends are increasing (and are statistically significant) over the Indian region and the increase is at a faster rate in the last 8 years compared to the previous ones. Trend from MODIS (OMI) was found to be 0.011 (0.002) year⁻¹ and 0.014 (0.006) year⁻¹ for the periods 2005–2012 and 2013–2021, respectively, over the Indian region. Increasing trends of AOD for zones selected in Indo-Gangetic Plains and South-India were found during 2005–2021, whereas for the desert zone, AOD trend has contrastingly became negative (2005–2012) to positive (2013–2021) in the recent years.

Keywords Desert · IGP · Anthropogenic · Trends · MODIS · OMI

Satellite-based monitoring of aerosols is useful to understand their spatial and temporal variability. Aerosol distribution shows large variations on daily, seasonal and inter-annual scales specifically in a country like India, owing to the short lifetimes, heterogeneity in the sources, and dependency of aerosols on the meteorological conditions. In addition, the Indian sub-continent exhibits large variability in vegetation cover and topography that might affect the aerosol distribution. Further, the aerosol retrievals from different satellite sensors may vary at regional and seasonal scales because of differences and uncertainties in calibration, sampling, cloud screening, treatment of the surface reflectivity and aerosol microphysical properties. To this end, a combination of satellite measurements can be used to examine the changing levels of aerosols with a greater reliability.

In this paper, we have analyzed the trends of Aerosol Optical Depth (AOD) over the Indian region during pre-monsoon season using datasets from two satellite sensors, i.e., Moderate Resolution Imaging Spectroradiometer (MODIS) onboard *Aqua* and Ozone Monitoring Instrument (OMI) onboard *Aura* platforms. We have used the combined Dark Target Deep Blue (DTDB) AOD estimates at 550 nm from MODIS; and the Ultra-Violet (UV) algorithm (OMAERUV) AOD retrievals at 500 nm from OMI. Though the standard quality assured Level 3 data products have been utilized from both the sensors, however, those might be affected by the uncertainties due to issues in the instrument calibration, data sampling, cloud screening and algorithm accuracy. Following this, it can be noted that the expected error (EE) of AOD from MODIS over land is within ± (0.05 + 0.15 * AOD) for Dark Target retrievals and ± (0.03 + 0.20 * AOD) for Deep Blue algorithm; while OMI AOD estimates are associated with retrieval uncertainty corresponding to (largest of) 0.1 or 30% (Anh et al., 2014; Bilal & Nichol, 2017; Kaufman et al., 1997; Remer et al., 2005; Torres et al., 2007, 2013; Wei et al., 2019). The AOD variability is studied for the last 17 years.
when there is frequent transportation of mineral dust from
industrial activities) mixed with the contribution from the
pogenic factors (biomass burning, vehicular emissions and
loading based on the complex combination of anthro-
region demonstrates a significant variability in aerosol
ization/industrialization and growing energy demands. This
region demonstrates a significant variability in aerosol
loading based on the complex combination of anthropo-
ogenic factors (biomass burning, vehicular emissions and
industrial activities) mixed with the contribution from the
natural sources, particularly in the pre-monsoon season
when there is frequent transportation of mineral dust from
the Thar Desert region (Mehta, 2015). Selection of Zone 2
is based on the dominance of natural aerosols as it lies in
the desert dust dominated region in the Indian sub-conti-
nent. During the pre-monsoon period, there is transport of
mineral dust from the Thar Desert and the Middle-East to
the northern and north-western India by south-westerly
summer winds (Dey et al., 2004). Over Zone 3, cleaner air
is generally expected when compared with Zone 1, but
rapid industrialization and urbanization is leading to large
amount of anthropogenic aerosols in this region. In addi-
tion, higher temperatures during pre-monsoon months play
an important role in heating and lifting the loose soil with
association of wind speed.

Spatial variation of averaged AOD (2005–2021) over
the Indian region using MODIS and OMI data during
March, April and May months is shown in Fig. 1b. It can
be seen that during pre-monsoon season, there is a high
aerosol loading over the northern part of the county due to
meteorological factors explained earlier. North-east region,
however, shows high aerosol loading which might be
attributed to the frequent forest fires during the pre-monsoon
months along with the cloud contamination due to cloud cover which mostly prevail over the region during
pre-monsoons (Pathak et al., 2012; Sahu et al., 2015).
Southern peninsular region shows low aerosol loadings
during the pre-monsoon season. A general trend of
increasing AOD from March to May can be attributed to
the fact that as the heat increases from March to May,
lifting of loose soil owing to strong winds becomes more
prominent along with the mixing of aerosols from anthro-
pogenic activities (Mehta, 2015). The values of mean AOD
(2005–2021) over the Indian region from (MODIS, OMI) is
found to be (0.40, 35) during pre-monsoon period with the
monthly averages of (0.37, 0.30) for March, (0.39, 0.37) for
April and (0.43, 0.37) for May, respectively. Figure 1c
shows the scatter plot for spatial correlation between the
AOD values from MODIS and OMI. The values of cor-
relation (R) were found to be 0.70, 0.55 and 0.64 for the
months of March, April and May, respectively. It is worth
noting here that highly correlated pixels were found to be
associated with low surface reflectivity areas and vice
versa.

The linear trend in AOD over the considered time frame
was observed in two equal halves of 8 years each, one
between 2005–2012 and the other between 2013–2021
(excluding 2020) to specifically see how the AOD trends
have changed during recent years as compared to
2005–2012. Year 2020 was excluded as there was a
nationwide lockdown over the Indian region [during
March, April and May (MAM)] due to Covid-19 and there
was a sudden halt of anthropogenic activities. This low
AOD loading over the Indian region observed in 2020
might affect the trends and hence, needs to be studied as a
special case (Mehta et al., 2021). Time series of the
pre-monsoonal mean AOD using both MODIS and OMI data
over Indian region is shown in Fig. 1d. The trends were
tested for statistical significance using the Student’s t-test
following the approach by Weatherhead et al. (1998). An
increasing trend is observed from data of both the sensors
in both the halves (2005–2012 and 2013–2021). Increasing
trend from MODIS is much more prominent than the trend
from OMI. Also, increasing trend in the second half
(2013–2021) is more than that of first half (2005–2012) for
both MODIS and OMI, and the trend is statistically sig-
ificant. Trend from MODIS is 0.011 and 0.014 year−1 for
first and second half, respectively, whereas trend from OMI
is 0.002 and 0.006 year−1. Further, time series of the sea-
sonal (MAM) mean AOD using both MODIS and OMI data
over the three zones is shown in Fig. 1e. For Zone 1, higher
positive AOD trends are found in the latter half of the
time period compared to the first half from both
MODIS and OMI. In Zone 2, though the overall AOD
trends for the entire time frame are negative, the nature of
trend has changed from negative to positive in the latter
half. The negative AOD trends in the period 2005–2012 are
in line with some previous studies done on desert dust
loading during pre-monsoon season associated with the
increasing rainfall (Pandey et al., 2017). However, in the
second half (2013–2021), before the year 2019, there was a
regular increase in the AOD values followed by a dip in
year 2019 and then again an increase in 2021. In this
context, some other studies (Ross et al., 2018; Sarkar et al.,
2019; Sharma and Majumdar, 2017) have indicated that
there has been an increase in the frequency of meteorolo-
gical droughts, heat waves, dust storms and maximum
surface temperatures over India, especially during the
recent years. As a large fraction of aerosols over zone 2 is
due to transported dust from the Arabian Sea (AS) (Gautam
et al., 2010); changes in wind speed over AS might also
influence the changes in the aerosol loading over Zone 2.
Interestingly, there has been a recent reversal in the global
terrestrial stilling of winds (Zeng et al., 2019); especially
over Asia, contrary to the findings in the previous decades.
These factors might have been responsible for the recent change in the nature of aerosol trend over the western Indian region; though exact reason could call for in-depth analysis of changes in natural and anthropogenic emissions; meteorological conditions and transport mechanism. On the other hand, trends are positive over both periods of 2005–2012 and 2013–2021 from both MODIS and OMI data over Zone 3.

We found that over the entire Indian region, in the last eight years, the trends have been increasing at a faster pace than the previous decade. In fact, for the desert region, where there had been a fall in the AOD values during the past years, recent years have witnessed an increasing trend. This increasing trend over the Indian mainland at a faster pace could be a matter of worry given the anthropogenic load along with the associated population of the country and its ever increasing demands. The lockdown period has set a classic example of how the aerosol burden can be reduced in light of decreasing emissions and could help the policy makers provide mitigation solutions in the coming years to control the increasing aerosol load.

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**Declarations**

**Conflict of interests** There are no conflicts of interests/competing interests.

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