Arabian Journal of Geosciences (2021) 14: 1256
https://doi.org/10.1007/s12517-021-07455-y

ORIGINAL PAPER

# Temporal and spatial variability in aerosol optical depth (550 nm) over four major cities of India using data from MODIS onboard the Terra and Aqua satellites

Swagata Payra [1,2] • Priyanshu Gupta [3] • Rajeev Bhatla [4] • Laaziz El Amraoui [5] • Sunita Verma [3,6]

Received: 9 October 2020 / Accepted: 25 May 2021 / Published online: 26 June 2021


## Abstract
The paper evaluates long-term (2007–2018) temporal and spatial variations in aerosol optical depth (AOD) over four major cities of India, i.e., Delhi, Kolkata, Chennai, and Jaipur, by using Collection 6, Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua Level-3, 1°×1° gridded dataset. Annual analysis reveals a significant increasing trend from 2007 to 2018 and aerosol loading in the Indo-Gangetic Plain (IGP). Interestingly, in Northern India, i.e., Delhi, AOD values peaked during monsoon season (0.95–1.05), whereas over Kolkata, Eastern India, higher AOD is observed in winter season (0.95–1.05). Chennai, Southern India, reflects low to moderate mean AOD during all the seasons. A prominent increase in AOD percentage from 2007 to 2018 is observed over Kolkata (39%), followed by Delhi (27.34%), Chennai (26.30%), and Jaipur (16.53%). Further, cumulative effects of different meteorological parameters along with 12-year mean AOD reflected a peak in aerosol concentration (0.82 ± 0.06) over Delhi, closely followed by Kolkata (0.81 ± 0.08) and then Chennai (0.43 ± 0.03) and Jaipur (0.43 ± 0.03). Results depict a significant increase in AOD due to a wide range of anthropogenic events and call for improved policy programs to tackle the increasing AOD emissions over these megacities in India.

**Keywords** Aerosol optical depth · MODIS · Trends · AOD tendency · Synoptic meteorology

## Introduction

Aerosols are one of the most important components of the atmosphere with a potential impact in modulating different climatic parameters. The atmosphere comprises of small colloidal particles with varying chemical nature suspended in the form of smoke, fog, and gas called as aerosols (Prospero et al. 1983). Origin source can be natural as well as anthropogenic. The major portion of natural aerosols comprises of wind dust, volcanic ash, and sea salts, while anthropogenic aerosols are emitted from agricultural waste burning and forests, industries, and fossil fuels. According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007), aerosol not only alters the radiation budget but also alters the cloud properties, atmospheric thermodynamics, and overall earth's climate system. Pachauri et al. (2014) reported the aerosol radiative forcing in the range of –0.9 (–1.9 to −0.1) W/m$^2$ for the period 1750–2011.

Optical and physical characteristics of aerosol significantly vary with geographical location; it may depend on their residence time and spatial distribution. Moreover, the optical and physical properties are also required to estimate the radiative effect of black carbon (Tripathi et al. 2005). Aerosol acts as a crucial factor in the heating/cooling process of the earth's surface resulting in cooling/warming of atmosphere. Optical properties of aerosol like aerosol optical depth (AOD),

Responsible Editor: Zhihua Zhang

✉ Sunita Verma
verma.sunita@gmail.com

[1] Department of Physics, Birla Institute of Technology, Mesra, Ranchi, Jharkhand, India

[2] Department of Physics, Birla Institute of Technology, Mesra, Jaipur Campus, Jaipur, Rajasthan, India

[3] Department of Environment and Sustainable Development, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

[4] Department of Geophysics, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

[5] CNRM, Université de Toulouse, Météo-France, CNRS, 42 Avenue Gaspard Coriolis, 31057 Toulouse, France

[6] DST-Mahamana Centre of Excellence in Climatology, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India

asymmetry parameter (ASY), and single scattering albedo (SSA) help to evaluate the direct aerosol radiative forcing (DARF) (Wang et al. 2015). Aerosol's effects are highly variable in space and time; therefore, both regional and global studies of aerosols are important (Prasad and Singh 2007; Bhatla et al. 2018; Soni et al. 2018). AOD quantifies the total aerosol loading in atmosphere. AOD is also an important parameter to examine the effect of aerosols on precipitation and radiation and a crucial metrics in assessing global climate change. In the recent decade, increasing rate of population, urbanization, and industrialization has significantly enhanced the AOD quantity over India.

Indian subcontinent is considerably affected by long-range transportation of aerosols (Ramanathan et al. 2001; Lawrence and Lelieveld 2010). Regional and global studies have been carried out using multiple satellite sensors and ground-based instruments, indicating the increase in aerosol loading specially in Indian regions (Beegum et al. 2008; Satheesh et al. 2008; Krishna Moorthy et al. 2013; Mitra et al. 2018; Gupta et al. 2020). Increasing concentration of suspended particles over urban areas has affected the visibility in most of the metropolitan cities like Delhi, Chennai, Kolkata, and Jaipur of the Indian subcontinent (Singh and Chauhan 2020). Several studies have reported the properties and characteristics of aerosol over different cities of India. Kumar (2014) observed an increase in AOD by >25% over Delhi, India, for the period 2003–2012. In Rohtak and Delhi during 2013, annual mean $AOD_{500nm}$ of 0.73 and 1.01 is observed (Taneja et al. 2017). Delhi during 2007 indicates the mean AOD (550nm) value of ~0.84±0.19 (ranging from 0.54 to 1.15), with anthropogenic aerosol contribution of 72%. The high AOD is observed during winter (84%), followed by post-monsoon (~78%) and summer season (~58%) (Srivastava et al. 2012).

Long-term (1980–2016) regional and global trends of AOD have been previously studied using MERRA-2, MISR, and MODIS/Terra datasets by Che et al. (2019) that suggested meteorological parameters can change a proportion of AOD variability between 20.4 and 72.8% for all the regions. Gu et al. (2018) studied the contributions of wind patterns and anthropogenic emissions to changing the AOD variability over the Beijing region. They reported that AOD slightly increased by 15.3% from 1980 to 2000 and by 36.9% from 2000 to 2006 and then gradually decreased from 2006 to 2014 by 10% due to the increase in green energy applications and government intervention over China. The Indian subcontinent has a wide range of aerosol characteristics due to different topographical features along with different climatic conditions (Habib et al. 2006). Several aerosol studies aimed to determine the climatic effects of aerosols over India (Dey and Tripathi 2008). Many scientific studies have validated the MODIS Terra and Aqua product against Aerosol Robotic Network (AERONET) over different cities of India. Payra et al. (2015) analyzed the correlation of both $MODIS_{Terra}$ and $MODIS_{Aqua}$ ($\tau_{MODIS}$) with AERONET ($\tau_{AERONET}$) for the years 2009–2012 over Jaipur city. During pre-monsoon season, an overestimation of $\tau_{MODIS}$ is observed within +0.06 ± 0.24, while it undergone underestimation −0.05 ± 0.18 during post-monsoon (October–November) and dry (December–March) season, respectively. At Kanpur city, evaluation of $AOD_{Aqua\text{-}MODIS}$ and $AOD_{Terra\text{-}MODIS}$ with AERONET revealed a high bias (Jethva et al. 2007). The comparative study of aerosol optical depth (AOD) retrieved by MODIS against AERONET observed at Kanpur shows good correlation ($R^2$ >0.7) for both Terra and Aqua within pre-launch uncertainty of ±0.05 ± 0.15. Over Nainital, a good correlation is seen for both Terra ($R^2$>0.8) and Aqua (>0.68) AOD datasets (Choudhry et al. 2012).

In light of the above, the present paper focuses to study the long-term (2007–2018) gridded MODIS AOD data for the first time. The study aims to delineate (1) the spatial and temporal changes with emphasis on four major cities of India. (2) The wind pattern and meteorological parameters such as temperature, relative humidity, and precipitation effect on the aerosol distribution have been analyzed for these major cities of India. The paper comprises of five sections. Sections 1, 2, and 3 deal with the Introduction, detailed description of data analysis, and site description. Further, Sect. 4 comprises of results with subsections 4.1 and 4.2 where spatial distribution of annual and seasonal mean AOD has been mentioned. Subsections 4.3 and 4.4 describe the monthly variation of mean AOD for the 12-year period by using radial plot and frequency distribution, respectively. In subsection 4.5, AOD tendencies have been calculated to know the prominent change in average AOD. Twelve-year average AOD as well percentage increase in AOD has been shown in subsection 4.6. Wind direction and wind speed for winter, pre-monsoon, monsoon, and post-monsoon season have been depicted by a spatial plot in subsection 4.7; further cumulative effect of mean AOD along with mean temperature and RH is shown by subsection 4.8. Finally, Sect. 5 concludes the main points drawn from the study.

## Data source and methodology

The Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) data has been retrieved from NASA's GIOVANNI website (http://giovanni.gsfc.nasa.gov/giovanni/). MODIS instrument is aboard the Terra and Aqua satellites. Terra passes across the equator from north to south in the morning (descending node), while Aqua crosses the equator from south to north in the afternoon (ascending node). They capture data in 36 spectral bands with wavelength ranges from 0.4 to 14.385 μm. It has a spatial resolution of 250m, 500m, and 1km. MODIS retrieve the aerosol characteristics within 0.47 to 2.12 μm of wavelength. The present study uses MODIS Terra (MOD08_D3 v6.1) and Aqua (MYD08_D3v6.1) level 3 product at a spatial resolution of 1° ×1°.

The datasets have been taken from Combined Dark Target and Deep Blue mean AOD at 550 nm for land and ocean. Further, average of both MODIS Terra and Aqua daily mean AOD datasets is used for the monthly, annual, and seasonal analysis over India. For seasonal analysis, climatological seasons have been taken as follows: post-monsoon season (October–November), winter season (December–February), pre-monsoon season (March–May), and monsoon season (June–September) following Mehta (2015). The meteorological parameters considered for the present study are wind speed, temperature, and relative humidity (RH). The data of temperature and RH are taken from the Weather Underground (Soni et al. 2021). The winds have been plotted using reanalysis data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR).

## Study area

Rapid economic growth and population explosion over the Indian megacities have caused a wide range of anthropogenic events. Moreover, the burning of crop in open area during post-monsoon is also responsible for the haziness and foggy condition in the northern parts of India. Anthropogenic aerosols remain dominant, particularly in metropolitan and industrialized areas. In this study, the four metropolitan cities of India are selected from the four different parts of India, i.e., Chennai (13.1° N, 80.3° E) from the southern part, Jaipur (26.9° N, 75.8° E) from the western part, Kolkata (22.6° N, 88.4° E) from the eastern part, and Delhi (28.7° N, 77.1° E) from northern part of India. The geographical locations of the four Indian megacities (Chennai, Delhi, Jaipur, and Kolkata) are shown in Fig. 1. Chennai, the capital of Tamil Nadu, experiences tropical wet and dry climate, with average annual rainfall of 1300 mm (Dhiman et al. 2019), roughly covers an area of 426 $km^2$, and accounts approx. 10.3 million populations. Delhi the capital of India holds 28.9 million populations with only 1484 $km^2$ area. Delhi experiences a dry-hot summer with maximum and minimum temperatures of 45°C to 3°C and having average relative humidity of 56%. Jaipur, the capital of Rajasthan, lies toward the eastern boundary of the Thar Desert, and from the two sides, it has been surrounded by Aravalli Mountains (Verma et al. 2013; Soni et al. 2014). It has a tropical climate and holds about 3.7 million populations with only 484.6 $km^2$ areas. Kolkata the capital of West Bengal has a tropical wet-dry climate, covers an area of 205 $km^2$, and holds about 5.5 million of population. In Kolkata, annual average temperature lies between 19 °C and 30 °C with average RH of 47 to 83%. It experiences southwest monsoon with annual rainfall of about 160 mm.

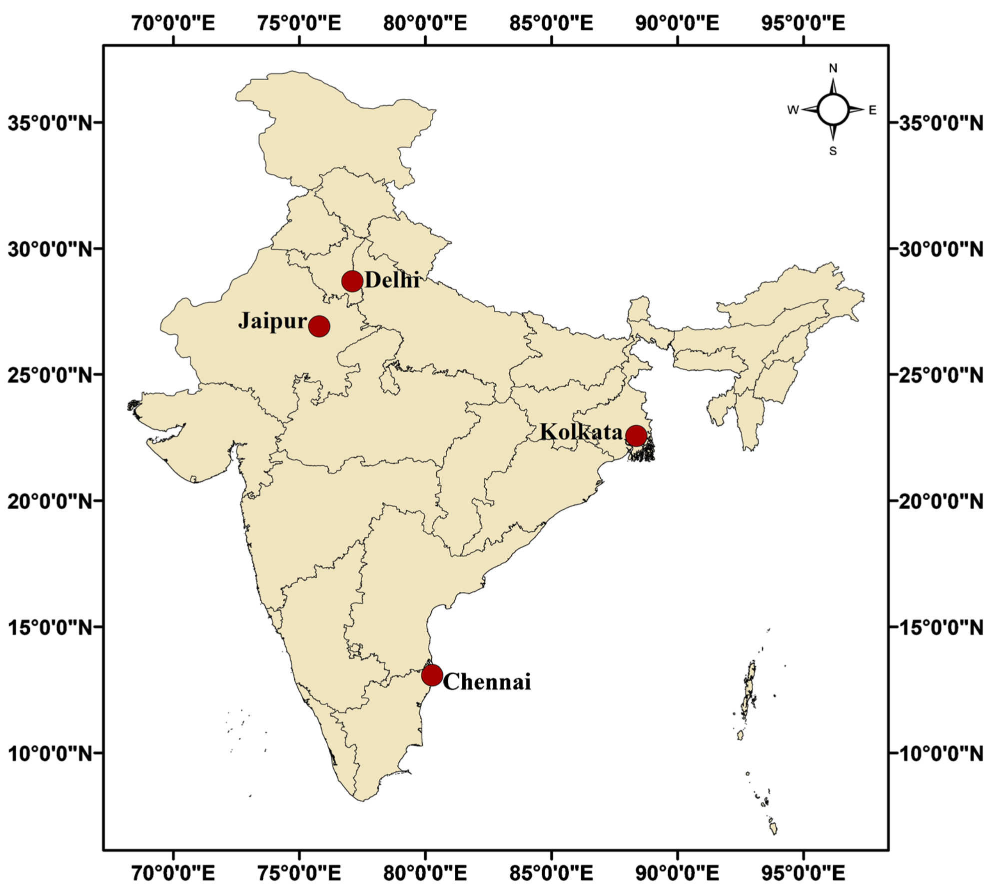


**Fig. 1** Study area map including four major cities of India: Delhi (28.7° N, 77.1° E), Jaipur (26.9° N, 75.8° E), Kolkata (22.6° N, 88.4° E), and Chennai (13.1° N, 80.3° E)

## Results and discussion

### Annual mean AOD

Annual mean aerosol loading (AOD) during the last 12 years (2007–2018) over four major cities of India, Chennai, Delhi, Jaipur, and Kolkata, is shown in Fig. 2. Significant increase in AOD concentration captured by combined MODIS Aqua and Terra is observed from previous to recent years. Western and southern parts of India receive low annual aerosol concentration, whereas moderate values persist in the central part of India. North India specially the Indo-Gangetic Plain (IGP) shows maximum annual aerosol concentration which could be attributed to presence of the Himalayas toward its north, plain topography, metrological parameters specially the wind patterns, and highest anthropogenic emissions. Sharp increase in the aerosol concentration over the middle Indian region (Peninsular Plateau) is seen from 2016 to 2018. Relatively similar values or no change in AOD values is seen for the Himalayan region throughout the study period. Delhi experiences higher AOD values (>0.77) in 2016 and 2018 that may be due to increase in biomass and fossil fuel burning. Kolkata, being highly urbanized and densely populated, shows maximum increase from 2007 to 2018. Moreover, high aerosol loading (>0.84) especially in recent years, i.e., 2015, 2016, 2017, and 2018, is clearly observed in Fig. 2, whereas low AOD, especially over IGP (0.63–077), is observed in 2007. Mean annual AOD over Jaipur city was found to be moderate, i.e., 0.30±0.05, whereas Chennai lies toward southern part of India showing mean AOD within 0.40±0.05. These significant increasing trends almost over all the locations of India are attributed to natural or anthropogenic sources or a combination of both.

### Seasonal mean AOD

Spatial variations of seasonal mean AOD derived from combined MODIS Aqua and Terra during 2007–2018 over India, especially for Chennai, Delhi, Jaipur, and Kolkata, are shown in Fig. 3. Overall, monsoon season reflects high AOD values (0.15–1.15) in all selected cities of India. In Delhi during winter, overall AOD remains around 0.75–0.85, while it became maximum during monsoon season (0.95–1.05). In premonsoon season, dust activities affected by soil moisture,

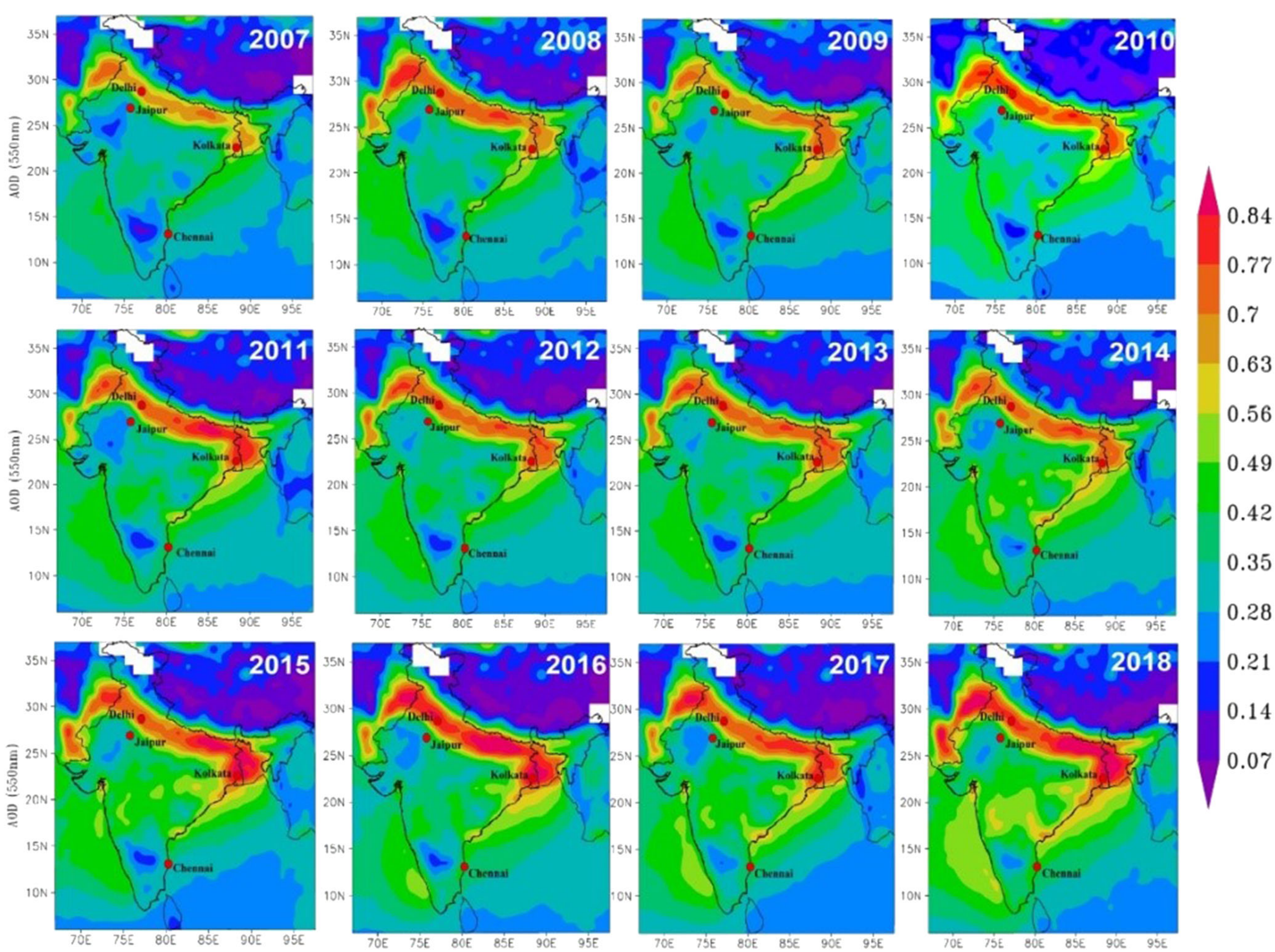


**Fig. 2** Distribution of annual mean AOD derived from Level-3 MODIS gridded datasets (1°×1°) during 2007–2018 over major cities of India

wind speed, rainfall, and onset of monsoon cause an increase in AOD which maximizes in monsoon season (Gautam et al. 2009). During post-monsoon, a mean AOD value (0.85–0.95) is seen due to blow of crop residues by northwesterly wind, coming from Punjab and Haryana (Sharma et al. 2010; Tiwari and Singh 2013). Jaipur experiences high aerosol loading (0.35–0.45) in the pre-monsoon and monsoon seasons likely due to desert dust and hygroscopic growth of aerosol particle and strong winds from the southwest, respectively. However, low AOD values (0.10–0.25) are observed during post-monsoon season for the possibility of wet deposition. In winter, mean AOD in the range of 0.25–0.35 is observed. In Kolkata during winter, high mean AOD value is seen (0.95–1.05) which is probably caused by local burning and stable atmosphere. Over IGP from west to east, increasing pattern in aerosol loading has been observed that may be due to wind and stable atmosphere. Compared to other regions during pre-monsoon season, Kolkata shows high AOD (0.55-0.75), due to presence of high humidity which helps in hygroscopic growth, whereas in monsoon season, decrease in aerosol loading is observed from west to east IGP that may be due to wet removal of aerosol particles. Coastal regions of India experience minor changing effects with season as they have lower aerosol concentration throughout the year. In Chennai, moderate to low mean AOD is observed for all the seasons.

## Monthly variation

Monthly mean AOD is shown as radial plot in Fig. 4. Irregular ring pointed in 12 directions indicates particular month, while different colors specify each year. Along with the size of the ring, AOD values increase from center to periphery. The different AOD values in different cities are observed. Relatively similar value of AOD (~0.4) in February and large fluctuations (0.4 – 0.7) during the month of May to June and October are observed over Chennai. The Chennai's weather is warm, and due to strong see breeze, pollution dispersed well for higher planetary boundary layer height. So, the value of AOD in Chennai is less but not in other two metro cities, i.e., Delhi and Kolkata. High AOD values (1.1–1.8) during July and August are seen for Delhi. Jaipur experiences high aerosol loading (0.6–0.8) in the month of August throughout the study period except for June 2008

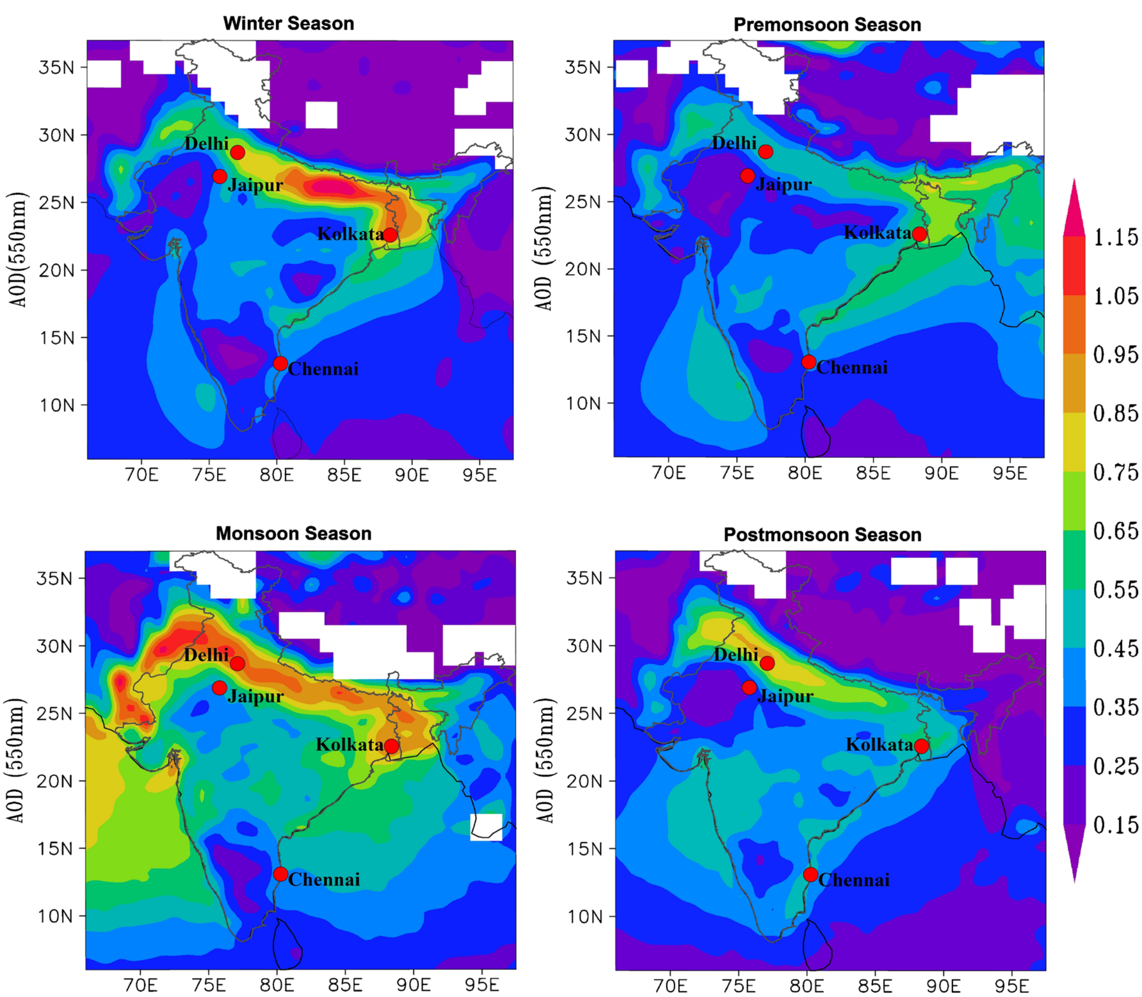


**Fig. 3** Spatial distribution of seasonal AOD derived from combined MODIS Aqua and Terra, Level-3 product at 550 nm over India

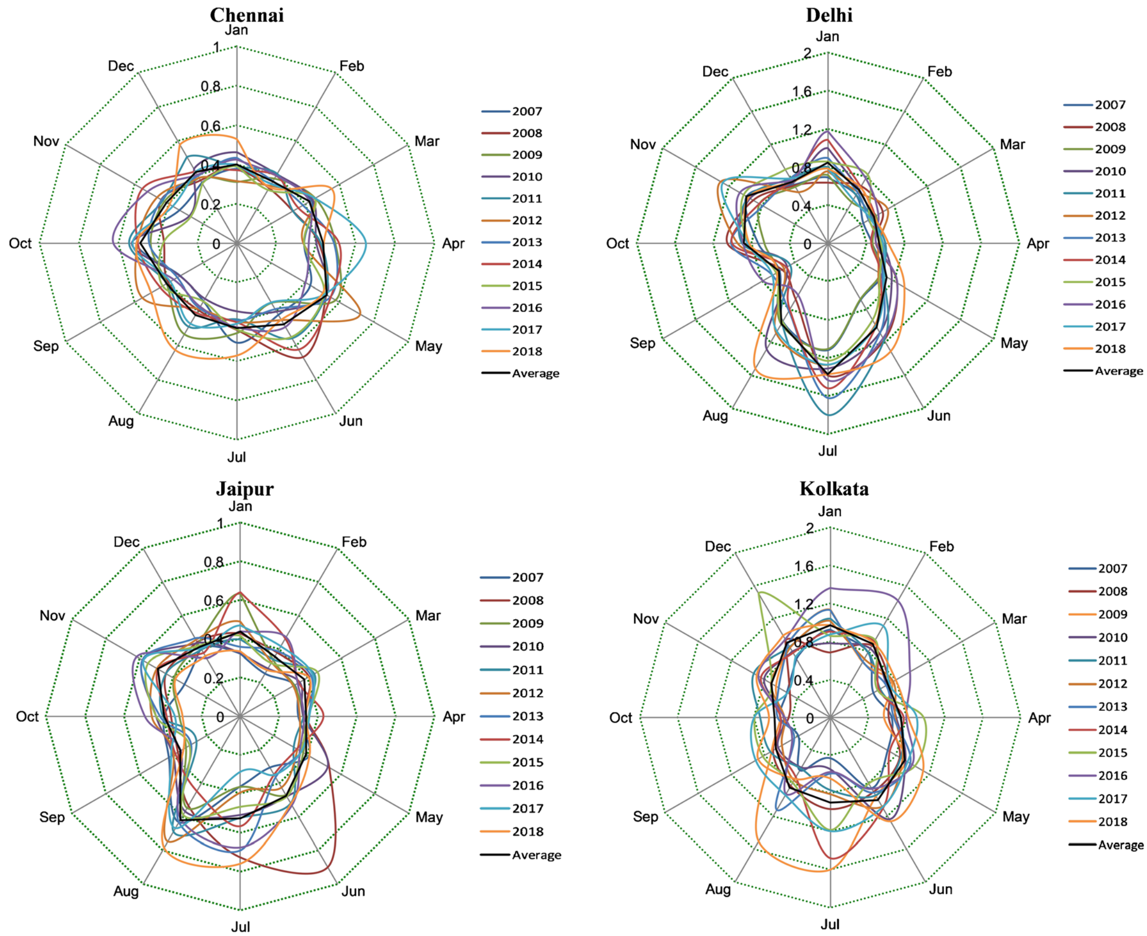


Fig. 4 Monthly mean AOD derived from combined MODIS Aqua and Terra product during 2007–2018 over Chennai, Delhi, Jaipur, and Kolkata

when it reached 0.9. In Delhi, AOD is dominated by dust activities in pre-monsoon season followed by rainfall, soil moisture, wind speed, and monsoon onset which leads to increase in AOD, and it becomes maximum in monsoon season (Gautam et al. 2009). The high AOD in monsoon can be due to cloud cover. The variation over Jaipur sites is mainly caused by the dust aerosols (Verma et al. 2013). The average AOD in Kolkata ranges from 0.8 to 1.0, with high average AOD value (~1.6) in July (2018), August (2018), and December (2015).

## Frequency distribution

Frequency distribution histogram of AOD over the selected cities in India is shown in Fig. 5. Chennai and Jaipur experience lower concentration of AOD; on the other hand, Delhi and Kolkata experience higher concentration of AOD. Frequency distribution of AODs for Chennai shows that 95% of the total aerosol concentration lies below 1.0 AOD value and more than 50% of the aerosol loading lies between the ranges of 0.20 and 0.50 AOD values. Similarly, over Jaipur, 85% of the total aerosol load lies below 1.0 AOD value, and more than 55% load lies between the ranges of 0.1 and 0.40 indicating low level of aerosol concentration in Jaipur in comparison to Delhi and Kolkata. Low levels of AOD in Jaipur are prominent. Jaipur lies in a semi-arid region which results in the natural dust aerosol throughout the year (Verma et al. 2013; Srivastava et al. 2012), whereas, in the case of Delhi, more than 30% of the total aerosol concentration lies above 1.0 AOD value indicating the dominance of high concentration of aerosol. This may be due to the larger population and traffic load emitting large amount of aerosol and due to the biomass burning in nearby areas. Kolkata also seems to be more affected by larger concentration of aerosols as more than 35% of AOD values lies above 1.0. This may be due to the natural (hygroscopic growth) as well as anthropogenic (industrial and traffic emitted) sources. Overall, Jaipur is least affected by the higher concentration of aerosol followed by Chennai, Delhi, and Kolkata, respectively.

## AOD tendencies

Annual and seasonal AOD tendencies (%) for 12-year period (2007–2018) computed by combined MODIS Terra and Aqua product are shown in Table 1. Annual AOD tendencies are defined as difference of last 6-year annual mean AOD (2013–2018) and first 6-year annual mean AOD (2007–2012) divided by first 6-year annual mean AOD (2007–2012). AOD tendencies help to know the prominent changes occurred in average aerosol loading

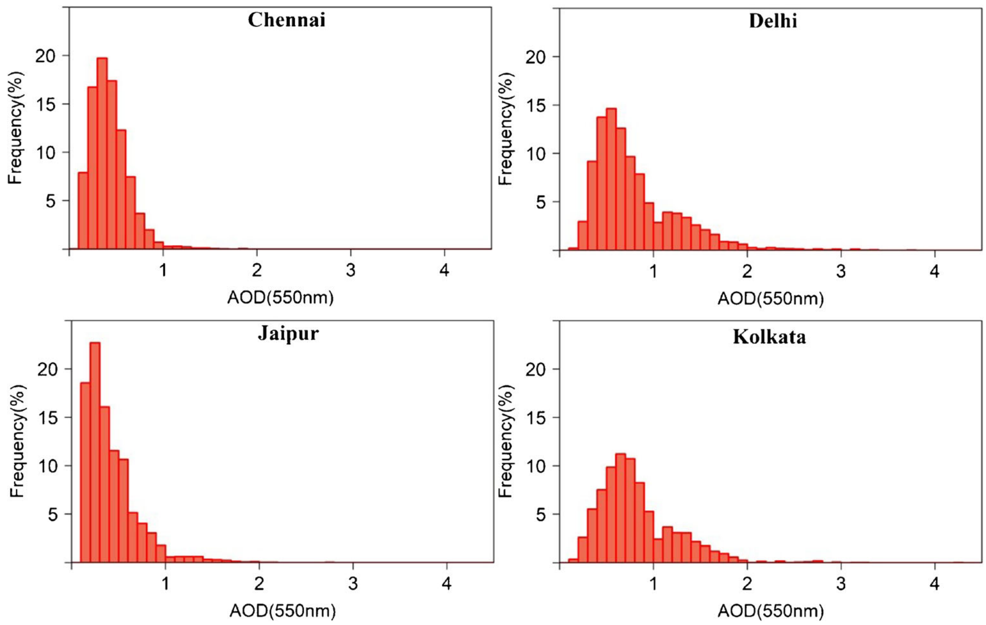


**Fig. 5** Frequency distribution plot of AOD for 12-year averaged data over Chennai, Delhi, Jaipur, and Kolkata

in last or first half of the past 12 years (2007–2018). Annual mean AOD reflects increasing tendencies for all the stations, i.e., Delhi (6.86%), Kolkata (12.20%), Chennai (4.07%), and Jaipur (3.0%). Seasonal analysis reveals significant increasing tendencies during winter season especially over Delhi (12%) and Kolkata (15.9%), which indicates an increase in anthropogenic activities over these two cities in recent years. In pre-monsoon season over Delhi and Jaipur, no change in AOD tendencies is observed, whereas an increase in AOD tendency is observed over Kolkata by 15.80%. In monsoon season, all the cities recorded increasing AOD tendencies, Delhi (4.74%), Kolkata (3.50%), and Chennai (4.80%), except Jaipur (−2.21%) where deceasing tendency is observed as a consequence of rainfall increments which help to wash out the air pollutants.

## Average AOD and percentage increase in AOD for the period 2007–2018

Twelve-year (2007–2018) mean AOD of combined MODIS Aqua and Terra product is shown by box-whisker plot in Fig. 6. Delhi shows mean AOD of 0.82 ± 0.06 during 12-year period of 2007–2018, whereas in Kolkata, mean AOD with standard deviation of 0.81 ± 0.08 is obtained with maximum variability in their AOD values. Chennai indicates mean AOD with standard deviation value of 0.43 ± 0.03, and Jaipur shows an AOD value of 0.43 ± 0.03. However, percentage increase in mean AOD from 2007 to 2018 is shown by bar graph; maximum increase in aerosol load (39%) from 2007 to 2018 is obtained over Kolkata, followed by Delhi which reveals an increase in AOD by 27.34%. Rawat et al. (2019) also reported 32% increase in AOD for the study period of 2001–2017 over Kolkata city. Chennai and Jaipur reveal 26.30% and 16.53% increasing percentage of aerosol load, respectively.

**Table 1** Annual and seasonal mean AOD tendencies calculated from the period 2007 to 2018 over four major cities

| City | AOD tendencies (%) | | | | |
|---|---|---|---|---|---|
| | Annual | Seasonal | | | |
| | | DJF | MAM | JJAS | ON |
| Delhi | 6.86% | 12% | 0% | 4.74% | 0% |
| Kolkata | 12.20% | 15.9% | 15.80% | 3.50% | 14.36% |
| Chennai | 4.07% | 2.02% | 1.30% | 4.80% | 4.50% |
| Jaipur | 3.0% | 4.08% | 0% | -2.21 | 4.90% |

Kolkata, Delhi, and Chennai are metro cities with more than 10 million population and the population density more than 25000 persons per km$^2$. This put huge demand on transport, available industries, etc. which contribute to the increase in air pollution. It's one of the reasons for high pollution, but Chennai's weather is warm, and due to strong see breeze, pollution dispersed well for higher planetary boundary layer height. So, the value of AOD in Chennai is less but not in other two metro cities, i.e., Delhi and Kolkata. Jaipur's population is around only 4 million, and the population density is around 6500 with less industrial activity. Thus, in Jaipur, low AOD values are seen.

## Wind pattern

India experiences diverse wind patterns during different seasons. Seasonal spatial variability of wind speed and direction for the period 2007–2018 at 10m height is shown in Fig. 7. The direction and intensity of wind depend on the pressure variation caused by difference in temperature (Swamy et al.

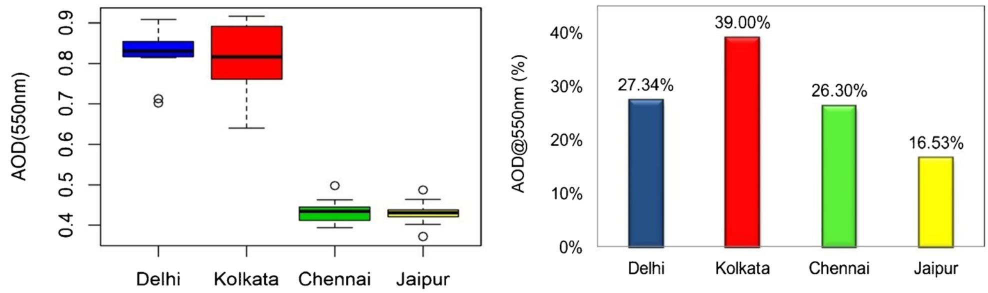


**Fig. 6** Cumulative mean AOD for the period 2007–2018 over Chennai, Delhi, Jaipur, and Kolkata is represented by box-whisker plot, and percentage increase in AOD from 2007 to 2018 is shown by bar graph

2017). During winter season, low-intensity wind blows from the north direction over most parts of India.

Prevailing northwesterly wind, lower wind speed, and stable condition during winter can lead to confinement of aerosol load over Jaipur and Delhi that originates over region due to biomass burning and other anthropogenic activities. The low temperature and lower boundary layer height during winter season trap the aerosols closer to the surface. Dense fog and hazy conditions are also observed due to confinement of anthropogenic aerosols such as sulfate and soot (Prasad et al. 2006; Gautam et al. 2007). During monsoon season, moisture-laden strong southwest winds blow from Indian Ocean and Bay of Bengal over Indian subcontinent. The presence of high humidity during this period causes hygroscopic growth of particles and increases the amount of AOD over coastal sites, e.g., Kolkata and Chennai, with increase in sea salt aerosols (Yang et al. 2019). During pre-monsoon season, wind blows from the northwest direction in northern part of India, while in

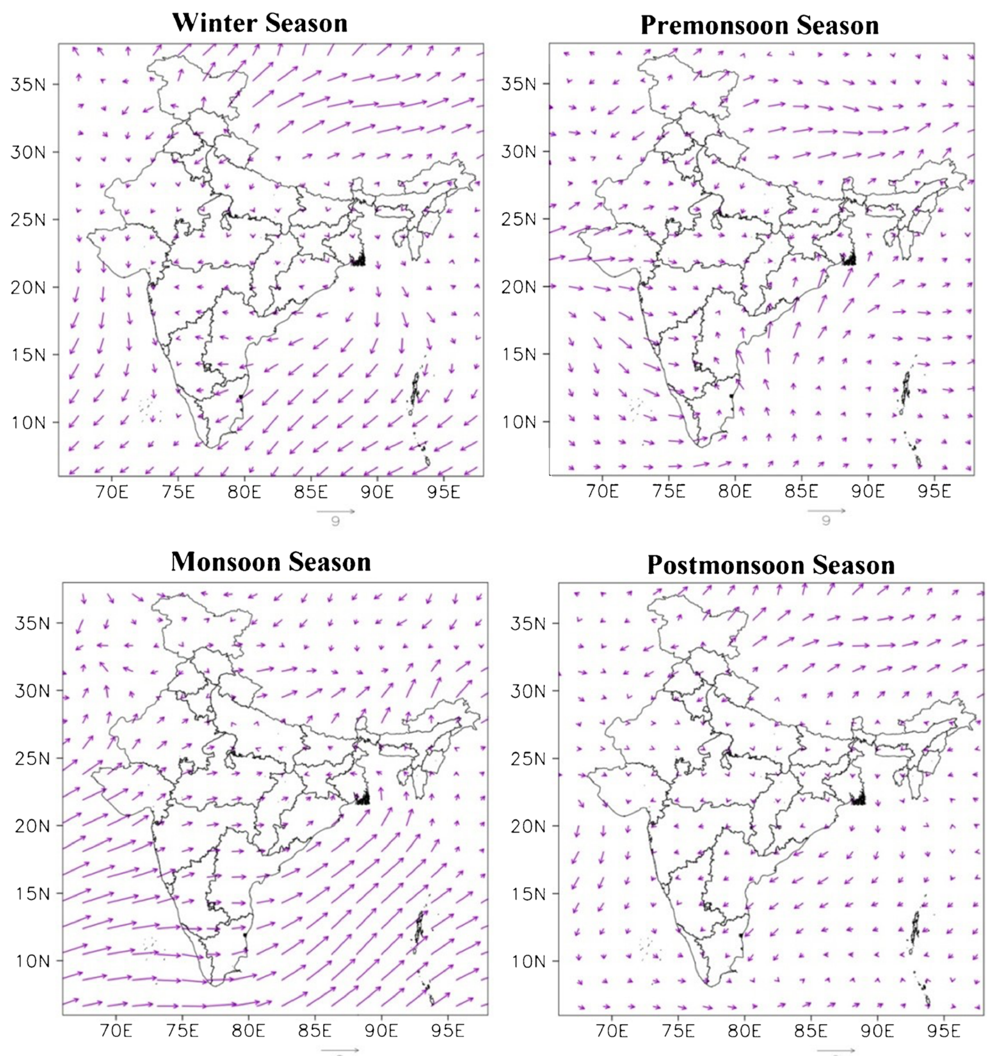


**Fig. 7** 12-year (2007–2018) average of winds (m/s) at 10 m height derived from NCEP/NCAR for winter, pre-monsoon, monsoon, and post-monsoon seasons, respectively

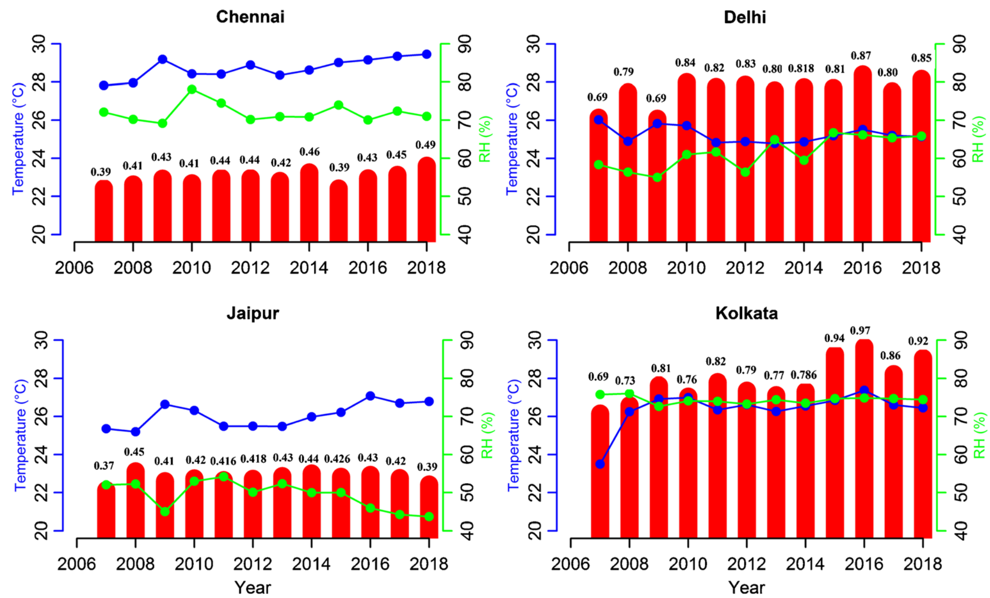


**Fig. 8** Cumulative effects of mean temperature (°C) and RH (%) taken from Weather Underground with combined MODIS Aqua and Terra AOD from 2007 to 2018

Arabian Sea and adjoining coast, the wind blows from southwest direction. Pre-monsoon wind causes heavy dust load over Jaipur and adjoining cities (Verma et al. 2013). Ramachandran et al. (2012) found a positive regression between AOD and wind speeds over Jaipur ($R^2$=0.60) showing that increase in wind speeds during 2000–2009 leads to 43% increase in AOD with respect to 2000. Post-monsoon season is characterized by retreating of wind pattern; it started shifting from southwest to northeast direction.

## Cumulative effect of mean temperature (°C) and RH (%) along with AOD

Along with the wind pattern, meteorological parameters such as temperature, relative humidity, and precipitation also have great effect on the aerosol distribution (Hoppel et al. 1994; Eck et al. 2012).

The climatological pattern of the annual average temperature (°C) and relative humidity (%) obtained from WUnderground with annual average AOD values obtained from combined MODIS Aqua and Terra product for 12 years (2007–2018) period at selected locations is shown in Fig. 8.

It is evident that with increase in temperature, low value of AOD is found over Delhi and Jaipur (Fig. 8). Delhi and Jaipur indicate an inverse relation between AOD and temperature. The correlation is −0.54 for Delhi and −0.2 for Jaipur. However, high positive correlation of AOD with temperature is exhibited over Chennai (0.62) and Kolkata (0.60), when temperature is low. Jayamurugan et al. (2013) mentioned that coastal urban area air pollution mostly shows positive correlation with temperature. Chennai recorded maximum annual temperature of 29.45°C (2018) with AOD value of 0.49 and minimum temperature of 27.82 °C (2007) with AOD value 0.39, while in Delhi maximum and minimum temperatures of 26.03 °C (2007) and 24.78 °C (2013) are found with AOD value of 0.69 and 0.80, respectively. In Jaipur, maximum annual temperature (27.08°C) is observed in year 2016 with AOD 0.42, and minimum temperature (25.19 °C) is seen during 2008 with AOD value of 0.45. Kolkata reported highest temperature of 27.37 °C (2016) with AOD of 0.97 while lowest temperature in 2007 (23.49 °C) with AOD of 0.69. Overall, the highest values of AOD are seen in the year 2016 for Delhi (0.87) and Kolkata (0.97), and relatively lower concentration of aerosol load (~0.40) is seen for Chennai and Jaipur. The AOD-temperature relationship is predominantly negative, meaning that higher AOD concentrations resulted in lower temperatures for both seasons over northeastern India (Roy 2008).

The highest value of RH in Chennai and Kolkata is likely due to their coastal extent as humidity is high near the coastal areas, whereas Delhi and Jaipur have the lowest percent of RH values due to its semi-arid topographical nature.

## Conclusions

This study deals with the spatial and temporal distributions of aerosol loading over four major cities of India, viz. Chennai, Delhi, Jaipur, and Kolkata, in terms of aerosol optical depth (AOD) by using MODIS onboard Aqua and Terra product at 1°×1° resolution for the period 2007–2018.

The major findings of the study are as follows:

- Annual variation of mean AOD reveals a significant increase in aerosol loading from previous to present year. Lower concentration of AOD was observed in 2007 with

sharp increase during 2016–2018. In comparisons to southern part of India, north region especially Indo-Gangetic Plain (IGP) shows high AOD value; this is due to high population and industrial growth and the presence of Himalaya which dominates the synoptic metrological condition.
- Seasonally, aerosol loading varies with topography. India as a whole reported maximum AOD during monsoon (0.15–1.15) followed by winter and post-monsoon seasons. During winter, maximum mean AOD (0.95–1.05) was found in Kolkata; this may be due to local burning and stable atmosphere, followed by Delhi with AOD in the range of 0.75–0.85. During monsoon season, maximum AOD is observed in Delhi (0.95–1.05), whereas wet removal from west to east causes low aerosol loading over Kolkata. Compared to other regions, Kolkata recorded maximum AOD during pre-monsoon season due to presence of high humidity that helps in hygroscopic growth, whereas over Chennai and Jaipur, low to moderate AOD is observed for all the seasons.
- An increase in AOD tendencies for 12-year period (2007–2018) has been observed for all the stations, i.e., Chennai (4.07%), Delhi (6.86%), Jaipur (3.0%), and Kolkata (12.20%). Seasonal analysis reveals maximum increase in aerosol tendencies during winter season especially over Delhi (12%) and Kolkata (15.9%), whereas in pre-monsoon, there has no change in AOD tendency observed for Delhi and Jaipur cities.
- Overall, among the four major cities, Delhi recorded maximum mean AOD (0.82 ± 0.06), followed by Kolkata (0.81 ± 0.08) and then Chennai (0.43 ± 0.03), whereas Jaipur (0.43 ± 0.03) recorded the least aerosol loading. However, maximum percentage increase in AOD from 2007 to 2018 is reported over Kolkata (39%), followed by Delhi (27.34%), Chennai (26.30%), and Jaipur (16.53%).
- Cumulative effects of mean AOD along with metrological parameters indicate lower values of AOD with corresponding temperature and higher RH for Chennai and Jaipur cities. Opposite trends are seen in the case of Delhi and Kolkata with higher AOD and lower temperature indicating excess load of anthropogenic aerosols and fine mode aerosol fraction.

**Acknowledgements** The authors wish to thank Moderate Resolution Imaging Spectroradiometer (MODIS) for providing the AOD datasets. The authors also like to acknowledge Wunderground (https://www.wunderground.com) and NCEP/NCAR reanalysis (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.htm) for provision of metrological data.

**Funding** The author would like to express sincere thanks to the Indian Space Research Organization under Respond program (ISRO/RES/3/806/19-20) and Ministry of Earth Science (MoES) Project (MoES/16/18/2017-RDEAS) for the financial support.

## Declarations

**Conflict of interest** The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

Beegum SN, Moorthy KK, Nair VS, Babu SS, Satheesh SK, Vinoj V, Reddy RR, Gopal KR, Badarinath KVS, Niranjan K, Pandey SK (2008) Characteristics of spectral aerosol optical depths over India during ICARB. J Earth Syst Sci 117(1):303–313

Bhatla R, Raj R, Singh A, Pipla B (2018) Association of AOD with extreme temperature and rainfall events over Varanasi during 2001-2014. Int J Earth Atmos Sci 5(1):36–46

Che H, Gui K, Xia X, Wang Y, Holben BN, Goloub P, Cuevas-Agulló E, Wang H, Zheng Y, Zhao H, Zhang X (2019) Large contribution of meteorological factors to inter-decadal changes in regional aerosol optical depth. Atmos Chem Phys 19(16):10497–10523

Choudhry P, Misra A, Tripathi SN (2012) Study of MODIS derived AOD at three different locations in the Indo Gangetic Plain: Kanpur, Gandhi College and Nainital. Annales Geophysicae (09927689) 30(10)

Dey S, Tripathi SN (2008) Aerosol direct radiative effects over Kanpur in the Indo-Gangetic basin, northern India: long-term (2001–2005) observations and implications to regional climate. J Geophys Res-Atmos 113:D04212. https://doi.org/10.1029/2007JD009029

Dhiman R, Vishnu Radhan R, Eldho TI, Inamdar A (2019) Flood risk and adaptation in Indian coastal cities: recent scenarios. Appl Water Sci 9(1):1–16

Eck TF, Holben BN, Reid JS, Giles DM, Rivas MA, Singh RP, Tripathi SN, Bruegge CJ, Platnick S, Arnold GT, Krotkov NA (2012) Fog- and cloud-induced aerosol modification observed by the Aerosol Robotic Network (AERONET). J Geophys Res Atmos 117(D7)

Gautam R, Hsu NC, Kafatos M, Tsay SC (2007) Influences of winter haze on fog/low cloud over the Indo-Gangetic plains. J Geophys Res Atmos 112(D5)

Gautam, R., Hsu, N.C., Lau, K.M., Tsay, S.C. and Kafatos, M. (2009). Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007. Geophys Res Lett, 36(7). doi:https://doi.org/10.1029/2009GL037641.

Gu X, Bao F, Cheng T, Chen H, Wang Y, Guo H (2018) The impacts of regional transport and meteorological factors on aerosol optical depth over Beijing, 1980–2014. Sci Rep 8(1):1–12. https://doi.org/10.1038/s41598-018-22803

Gupta P, Verma S, Bhatla R, Chandel AS, Singh J, Payra S (2020) Validation of surface temperature derived from MERRA-2 reanalysis against IMD gridded data set over India. Earth and Space Sci 7(1). https://doi.org/10.1029/2019EA000910

Habib G, Venkataraman C, Chiapello I, Ramachandran S, Boucher O, Reddy MS (2006) Seasonal and interannual variability in absorbing aerosols over India derived from TOMS: relationship to regional meteorology and emissions. Atmos Environ 40(11):1909–1921. https://doi.org/10.1016/j.atmosenv.2005.07.077

Hoppel WA, Frick GM, Fitzgerald JW, Larson RE (1994) Marine boundary layer measurements of new particle formation and the effects nonprecipitating clouds have on aerosol size distribution. J Geophys Res Atmos 99(D7):14443–14459

IPCC Climate Change 2007 (2007) The physical science basis, vol 996. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jayamurugan R, Kumaravel B, Palanivelraja S, Chockalingam MP (2013) Influence of temperature, relative humidity and seasonal variability on ambient air quality in a coastal urban area. Int J Atmos Sci 2013, Article ID 264046:7. https://doi.org/10.1155/2013/264046

Jethva H, Satheesh SK, Srinivasan J (2007) Assessment of second-generation MODIS aerosol retrieval (Collection 005) at Kanpur, India. Geophys Res Lett 34(19). https://doi.org/10.1029/2007GL029647

Krishna Moorthy K, Suresh Babu S, Manoj MR, Satheesh SK (2013) Buildup of aerosols over the Indian region. Geophys Res Lett 40(5): 1011–1014. https://doi.org/10.1002/grl.50165

Kumar A (2014) Long term (2003–2012) spatio-temporal MODIS (Terra/Aqua level 3) derived climatic variations of aerosol optical depth and cloud properties over a semi arid urban tropical region of Northern India. Atmos Environ 83:291–300. https://doi.org/10.1016/j.atmosenv.2013.10.030

Lawrence MG, Lelieveld J (2010) Atmospheric pollutant outflow from southern Asia: a review. Atmos Chem Phys 10(22):11017. https://doi.org/10.5194/acp-10-11017-2010

Mehta M (2015) A study of aerosol optical depth variations over the Indian region using thirteen years (2001–2013) of MODIS and MISR Level 3 data. Atmos Environ 109:161–170

Mitra AK, Parihar S, Bhatla R, Ramesh KJ (2018) Identification of weather events from INSAT-3D RGB scheme using RAPID tool. Current Science (00113891) 115(7):1358–1366

Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P (2014) Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri RK, Meyer LA (eds) Intergovernmental Panel on Climate Change (IPCC). Geneva, Switzerland, 2014, p 151

Payra S, Soni M, Kumar A, Prakash D, Verma S (2015) Intercomparison of aerosol optical thickness derived from MODIS and in situ ground datasets over Jaipur, a semi-arid zone in India. Environ Sci Technol 49(15):9237–9246

Prasad AK, Singh RP (2007) Comparison of MISR-MODIS aerosol optical depth over the Indo-Gangetic basin during the winter and summer seasons (2000–2005). Remote Sens Environ 107(1-2):109–119. https://doi.org/10.1016/j.rse.2006.09.026

Prospero JM, Charlson RJ, Mohnen V, Jaenicke R, Delany A c, Moyers J, Zoller W, Rahn K (1983) The atmospheric aerosol system: an overview. Rev Geophys Space Phys 21:1607–1629. https://doi.org/10.1029/RG021i007p01607

Ramachandran S, Kedia S, Srivastava R (2012) Aerosol optical depth trends over different regions of India. Atmos Environ 49:338–347

Ramanathan V, Crutzen PJ, Lelieveld J, Mitra AP, Althausen D, Anderson J, Andreae MO, Cantrell W, Cass GR, Chung CE, Clarke AD (2001) Indian Ocean experiment: an integrated analysis of the climate forcing and effects of the great Indo-Asian haze. J Geophys Res Atmos 106(D22):28371–28398

Rawat P, Sarkar S, Jia S, Khillare PS, Sharma B (2019) Regional sulfate drives long-term rise in AOD over megacity Kolkata, India. Atmos Environ 209:167–181

Roy SS (2008) Impact of aerosol optical depth on seasonal temperatures in India: a spatio-temporal analysis. Int J Remote Sens 29(3):727–740. https://doi.org/10.1080/01431160701352121

Satheesh SK, Moorthy KK, Babu SS, Vinoj V, Dutt CBS (2008) Climate implications of large warming by elevated aerosol over India. Geophys Res Lett 35(19). https://doi.org/10.1029/2008GL034944

Sharma AR, Kharol SK, Badarinath KVS, Singh D (2010) Impact of agriculture crop residue burning on atmospheric aerosol loading–a study over Punjab State, India. Annales Geophysicae (09927689) 28(2):367–379

Singh RP, Chauhan A (2020) Impact of lockdown on air quality in India during COVID-19 pandemic. Air Qual Atmos Health 13(8):921–928

Soni M, Payra S, Sinha P, Verma S (2014) A performance evaluation of WRF model using different physical parameterization scheme during winter season over a semi-arid region, India. Int J Earth and Atmos Sci 1(3):104–114

Soni VK, Bist S, Bhatla R, Bhan SC, Kumar G, Sateesh M, Singh S, Pattanaik DR (2018) Effect of unusual dust event on meteorological parameters & aerosol optical and radiative properties. Mausam 69(2):227–242

Soni M, Chandel AS, Verma S, Payra S, Prakash D, Holben B (2021) Aerosols properties over desert influenced locations situated in four different continents. Atmos Environ:118232

Srivastava AK, Singh S, Tiwari S, Bisht DS (2012) Contribution of anthropogenic aerosols in direct radiative forcing and atmospheric heating rate over Delhi in the Indo-Gangetic Basin. Environ Sci Pollut Res 19(4):1144–1158

Swamy G, Nagendra SS, Schlink U (2017) Urban heat island (UHI) influence on secondary pollutant formation in a tropical humid environment. J Air Waste Manage Assoc 67(10):1080–1091. https://doi.org/10.1080/10962247.2017.1325417

Taneja K, Attri SD, Ahmad S, Ahmad K, Soni VK, Mor V, Dhankhar R (2017) Comparative assessment of aerosol optical properties over a mega city and an adjacent urban area in India. Mausam 68(4):673–688

Tiwari S, Singh AK (2013) Variability of aerosol parameters derived from ground and satellite measurements over Varanasi located in the Indo-Gangetic Basin. Aerosol Air Qual Res 13:627–638

Tripathi SN, Dey S, Tare V, Satheesh SK (2005) Aerosol black carbon radiative forcing at an industrial city in northern India. Geophys Res Lett 32(8). https://doi.org/10.1029/2005GL022515

Verma S, Payra S, Gautam R, Prakash D, Soni M, Holben B, Bell S (2013) Dust events and their influence on aerosol optical properties over Jaipur in Northwestern India. Environ Monit Assess 185(9): 7327–7342. https://doi.org/10.1007/s10661-013-3103-9

Wang Z, Liu D, Wang Y, Shi G (2015) Diurnal aerosol variations do affect daily averaged radiative forcing under heavy aerosol loading observed in Hefei, China. Atmos Meas Tech 8(7):2901–2907. https://doi.org/10.5194/amt-8-2901-2015

Yang L, Mukherjee S, Pandithurai G, Waghmare V, Safai PD (2019) Influence of dust and sea-salt sandwich effect on precipitation chemistry over the Western Ghats during summer monsoon. Sci Rep 9(1): 1–13