[DOR: 20.1001.1.24766267.2022.7.4.6.1]
[DOI: 10.18502/jehsd.v7i4.11432]

Journal of Environmental Health and Sustainable Development

Aerosol Optical Depth Spatial and Temporal Variability Using Satellite Data Over Indian Major Cities

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ARTICLE INFO

ORIGINAL ARTICLE

Article History:
Received: 13 August 2022
Accepted: 20 October 2022

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Keywords:
Aerosol Optical Depth,
Atmosphere,
Health,
Meteorology,
Indian Cities.

ABSTRACT

Introduction: The study's main aim is to investigate the long-term variation of Aerosol Optical Depth (AOD). It also aims to show the relationship between meteorological parameters. This study evaluates long-term (2010 to 2021) special and temporal changes over major Indian regions using satellite-based data from NASA's Terra Satellite.

Materials and Methods: This study was carried out during 2010-2021 using MODIS data for long-term analysis. Variation of AOD with meteorological parameters was also performed to show the impact of these parameters (Temperature and Relative Humidity) on AOD by the MERRA-II model.

Results: Based on Terra AOD data, in all the studied regions, especially the eastern region (Kolkata), the mean AOD was high (0.9-1.2). In the western region (Mumbai, Ahmedabad, and Surat), the mean AOD was low to moderate during all seasons. Furthermore, the impact of meteorological parameters on AOD shows significant variation in average annual AOD in Kolkata (0.70 ± 0.09), while other regions reported lower than average AOD values during the study period. Mumbai and Surat had average AODs (0.44 ± 0.13), (0.45 ± 0.14), while Ahmedabad and Jaipur reported average AOD of 0.45 ± 0.14 and 0.23 ± 0.11 during the study period, respectively.

Conclusion: Generally, AOD values vary from season to season due to aerosol's optical and microphysical properties being affected by meteorological conditions and surface albedo. This study examined the spatial and temporal distribution of AOD over five major Indian cities.

Citation: Solank R, Pathak K. ***Aerosol Optical Depth Spatial and Temporal Variability Using Satellite Data Over Indian Major Cities***. J Environ Health Sustain Dev. 2022; 7(4): 1827-41.

Introduction

Aerosol concentrations in the atmosphere significantly impact both human health and indeed the earth's climate [1–4]. Researchers have become very interested in the field of atmosphere [5–7]. These effects go far beyond global warming, affecting ecosystems and populations all across the globe. Things we rely on and value, such as water, electricity, transportation, wildlife, agriculture, environment, and human health are all affected by climate change. Aerosols in the atmosphere have the ability to affect the climate system by the absorption and reflection of solar energy [8,9]. Aerosols can enter the atmosphere from anthropogenic or natural sources, as well as atmospheric chemical and physical processes [10]. Natural processes (such as soil dust, desert dust, sea salt, biogenic, and volcanic emissions) and anthropogenic activities (such as fossil fuel combustion, urban and industrial emissions, volatile organic compounds from vegetation, and agricultural waste burning) both contribute to the evolution of aerosol compounds in the atmosphere [11]. Aerosols are produced in one spot and then dispersed over vast distances by winds, causing impacts at locations far from the source [12]. On regional and global scales, research into aerosol properties is critical. However, aerosol data are spatially limited, and their effects on climate change are largely unknown [13].

Satellite remote sensing offers the benefit of providing spatial and temporal distributions of aerosol optical characteristics in this aspect. Previous studies have been conducted by [14] northeastern Asia (NEA), northern China (NC), southern China (SC), southeastern Asia (SEA), northwestern China (NWC), south Asia (SA), Middle East (ME), western Europe (WEU), Sahara desert (SD), central Africa (CF), eastern United States (EUS), and Amazon zone (AMZ) in the long-term (1980-2016) AOD trend using MISR, Moderate Resolution Imaging Spectrometer (MODIS) Aqua, and MERRA-2. They have suggested that in all the regions, meteorological factors can change the percentage of AOD variability from 20.4% to 78.2%. In addition, many studies have validated the MODIS products with AERONET (Aerosol Robotic NETwork) AOD over different Indian areas, and MODIS correlation was analyzed with AERONET over Jaipur city [15]. Seasonal means of AOD at 0.4 μm are found to vary from 0.36 (pre-monsoon) to 0.47 (monsoon) and from 0.07 (winter) to 0.17 (pre-monsoon) over Ahmedabad using a sun-photometer [16].

This study focused on long-term (2010-2022) variations of AOD over densely populated major Indian cities. The study aimed to demonstrate the temporal variations, emphasizing five significant Indian cities using the MODIS gridded mean AOD data. Finally, the study analyzed the distribution of AOD with a meteorological parameter, such as temperature (T) and relative humidity (RH), in the studied regions.

Study area

Indian megacities have rapid growth in terms of the economy, population, and industrial activity, causing many anthropogenic events. Five different significant cities were investigated in this study, represented in Figure 1. India is located on the equator's northern side. The area latitude and the longitude is 06.73° N and 35.50° N; respectively, the longitude is 68.11° E and 97.41° E. Most of the areas of Indian country have tropical climates because the tropic of cancer intercepts the country in the middle part. In this study, the daily-averaged AOD product from the MODIS satellite was used for five different Indian stations; Figure 1 and Table 1 show the geographical locations of the study regions, elevation from mean sea level, and population data according to census 2011 (https:// www .census2011.co.in/).

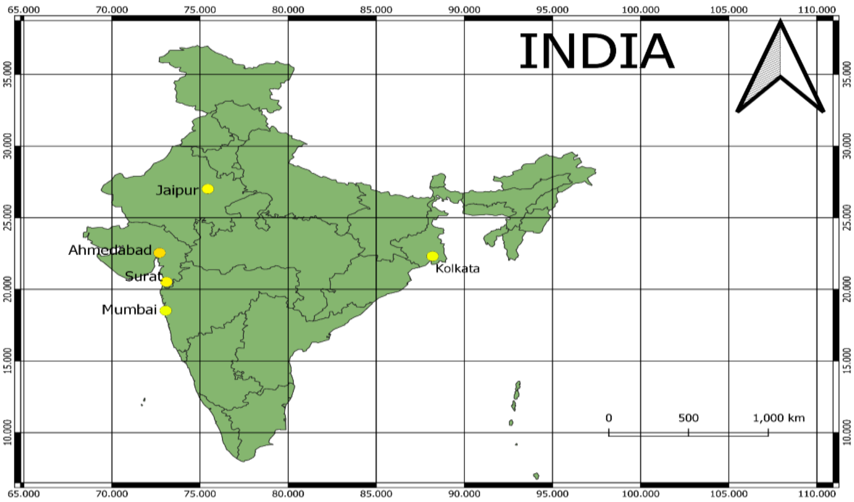

Figure 1: Geographical locations of the study regions (Kolkata, Mumbai, Ahmedabad Surat, and Jaipur)

Table 1: Details of the states, cities, and their locations (latitude, longitude, and elevation)

State	City	Location	Elevation [MSL]	Population	Population density
West Bengal	Kolkata	22.57° N, 88.36° E	9	44,96,694	24306
Maharashtra	Mumbai	19.07° N, 72.87° E	11	93,56,962	20980
Rajasthan	Jaipur	26.91° N, 75.78° E	390	3,046,163	9,700
Gujarat	Surat	21.17° N, 72.83° E	13	6,081,322	10052
Gujarat	Ahmedabad	23.02° N, 72.57° E	53	5,633,927	16,000

Note: MSL means Mean Sea Level

Kolkata (22.57° N, 88.36° E) is one of the most populated cities located on the eastern bank of the Hooghly River. It has a tropical wet-dry climate. Mumbai (19.07° N, 72.87° E) is one of the most populated cities and a large seaport area near the Arabian Sea with a tropical climate. Jaipur (26.91° N, 75.78° E) is the capital city of the Indian state of Rajasthan. It is located on the Thar Desert's eastern boundary, and it has been covered by Aravalli Mountain from the two sides [17,18], which is also one of the most populated cities. It has a hot semi-arid climate with long, sweltering summers and short, mild, to warm winters. Surat (21.17° N, 72.83° E) is one of Gujrat's diamond and textile industrial hubs. It has a tropical savanna-type climate with a large seashore area and is located near the bank of the Tapi River. Out of five different Indian regions, Ahmedabad (23.02° N, 72.57° E) has emerged as one of India's significant economic and industrial hubs. Ahmedabad has a hot semi-arid-type climate.

Materials and Methods

Remote sensing data provide a better understanding of aerosol characteristics at a large scale and are available in a wide range, while ground-based observation is very limited. MODIS products under go different processing levels including geo-located and calibrated at level 1.0, products derived from geophysical data at level 2.0, and gridded time-averaged products at level 3.0 and collections [19]. The data were obtained from NASA's GIOVVANI website (http://giovanni.gsfc.nasa.gov/giovanni/). The MODIS onboard Terra/Aqua satellites measure reflected sunlight from the surface and the Earth's atmosphere, as well as emitted thermal radiation at wavelengths of 36, to give daily global information on Earth's atmospheric aerosol parameters [20]. MODIS has a swathe resolution of around 2330 km and circles the Earth 14 to 15 times daily to cover the globe. Two separate techniques are used to retrieve aerosol properties over land and water, and these algorithms are constantly being refined [21,22]. MODIS aerosol science team articles contain a detailed description of the MODIS aerosol retrieval algorithms [23,24]. MODIS AOD parameter is substantially validated regionally and globally and has been used for aerosol studies [11,25]. The predicted errors in obtaining these parameters are less than ± 0.05, and the uncertainties are mostly attributable to the non-spherical size distribution of aerosols and different techniques employed for land and ocean [26]. Because of the wide range of data products available, the MODIS satellite products were used for AOD measurement in this study. The devices use spectral observations by reflected solar radiation, radiative transfer calculations, and AOD level calculated by the aerosol models, as shown in Figure 2. Both EOS satellites (Aqua and Terra) of MODIS collect the AOD level two times daily with high spatial resolution on a near-global basis (10 km^2) [26]. A precise choice of satellite AOD products over a certain location is critical for accurately calculating the aerosol level in that extent [27]. Compared to ground-based observations, satellite-based observations make available information over a greater spatial domain [5]. Furthermore, satellite-based monitoring allows for the systematic recovery of aerosol optical characteristics at worldwide and regional scales. According to Lee et al. study [28], satellite-based

[DOR: 20.1001.1.24766267.2022.7.4.6.1]
[DOI: 10.18502/jehsd.v7i4.11432]

monitoring can be used to supplement ground monitoring stations, particularly in areas with a limited number of monitors. The present study used MODIS Aqua and Terra products to look at AOD loading over Indian regions.

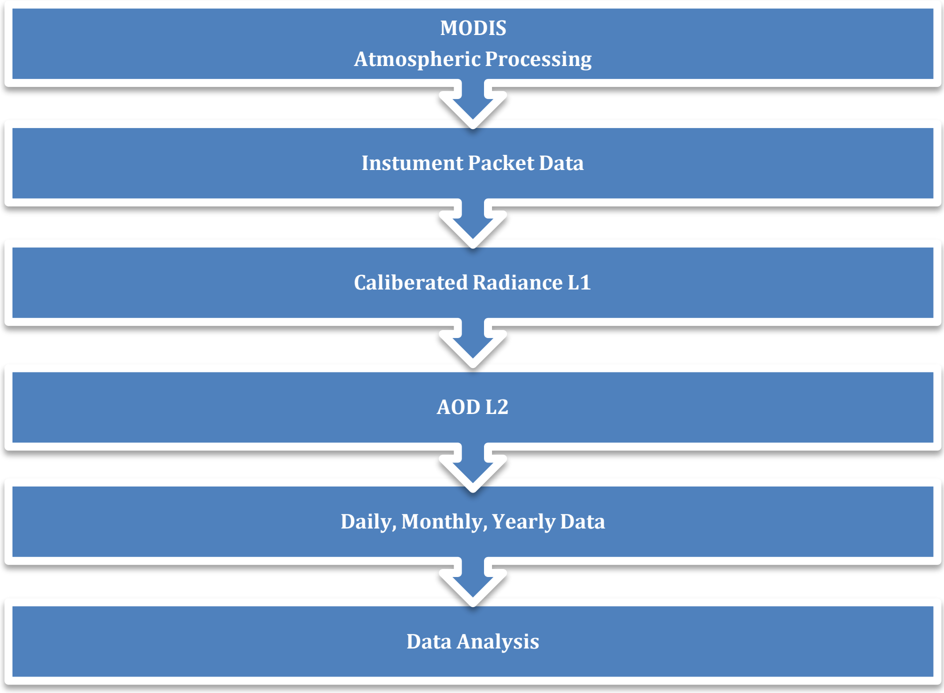

Figure 2: Schematic diagram of MODIS data processing

The long-term data extracted from 2011 to 2020 were used to analyze the monthly, seasonal, and annual average AOD values. For this study, the daily Level-2 MODIS/Terra (MYD08) Dark Target retrieval technique Collection-6 3-km AOD products were used across the Indian region. The cloud mask and Level 1B calibrated radiances are used to create MODIS atmospheric profiles. These profiles, which are created globally for clear skies only, comprise total column estimates of the tropospheric and stratospheric ozone, temperature and moisture profiles of the atmosphere, indicators of atmospheric stability, and total column amounts of water vapor. Atmospheric products at level 2 give information on aerosol and cloud characteristics. Global optical thickness and size distribution of atmospheric aerosols across land and oceans are included in the MODIS aerosol package. The daily data were used to compute monthly, seasonal, and annual averages over the entire period of the study. For seasonal analysis, we have climatological season divided into four main seasons, including winter or dry season (December to February), pre-monsoon season (March to May), and monsoon or rainy season (June to September), and post-monsoon (October to November). Temperature, relative humidity, and wind speed data were considered meteorological parameters. The temperature and relative humidity data were taken from Goddard Earth Sciences Data and Information Services Center MERRA-II (https://www.soda-pro.com/web-services/meteo-data/merra).

Results

Analysis of annual mean variations in Aerosol Optical Depths (AOD)

At 550 nm, the annual average AOD obtained from January 2010 to December 2021 (twelve-year data) from the MODIS instrument on the Terra satellite is shown in Figures 3 and 4 and Table 2. AOD concentration significantly increased throughout the study period from the previous year to the recent year. Figures 3 and 4

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demonstrate that the western and southern regions show low AOD concentrations annually, while the central Indian region shows moderate AOD concentrations. The Indo-Gangetic Plain (IGP) in North India, in particular, exhibits the highest yearly aerosol loading, which may be related to its northern Himalayas, simple topography, and metrological factors, particularly wind patterns, and the most anthropogenic emissions. Relatively low to moderate variations were observed over the Himalayan region throughout the study period.

Due to an increase in the combustion of biomass and fossil fuels, urbanization, and high population, Kolkata experienced higher AOD values (> 0.7) during the study period compared to other regions except 2020, as shown in Figure 4. Compared to the eastern region of Kolkata, in the Western region of Mumbai, Surat, Ahmedabad, and Jaipur, the mean annual AOD was determined to be moderate, at (0.39 ± 0.12). However, the 2021 western regions, especially Ahmedabad, Surat, and Mumbai, showed a higher AOD concentration (0.86).

Table 2: Average annual variation of AOD with standard deviation during 2011-2021

Years	KLK		MUM		ST		AHM		JAI	
	Avg.*	**Std.****	**Avg.**	**Std.**	**Avg.**	**Std.**	**Avg.**	**Std.**	**Avg.**	**Std.**
2011	0.68	0.15	0.36	0.06	0.34	0.08	0.37	0.17	0.22	0.13
2012	0.65	0.19	0.38	0.07	0.38	0.07	0.44	0.14	0.26	0.10
2013	0.65	0.20	0.38	0.09	0.42	0.12	0.43	0.12	0.21	0.08
2014	0.66	0.21	0.42	0.08	0.46	0.14	0.46	0.14	0.21	0.11
2015	0.80	0.26	0.47	0.16	0.48	0.13	0.48	0.15	0.23	0.10
2016	0.78	0.42	0.36	0.09	0.41	0.09	0.40	0.08	0.26	0.12
2017	0.73	0.18	0.41	0.04	0.47	0.13	0.48	0.15	0.21	0.10
2018	0.79	0.15	0.45	0.09	0.48	0.09	0.47	0.11	0.25	0.10
2019	0.74	0.21	0.45	0.07	0.46	0.12	0.50	0.16	0.26	0.18
2020	0.70	0.23	0.43	0.09	0.44	0.14	0.49	0.22	0.24	0.11
2021	0.83	0.29	0.52	0.09	0.59	0.22	0.50	0.16	0.23	0.13

*Avg: Average
**Std: Standard Deviation

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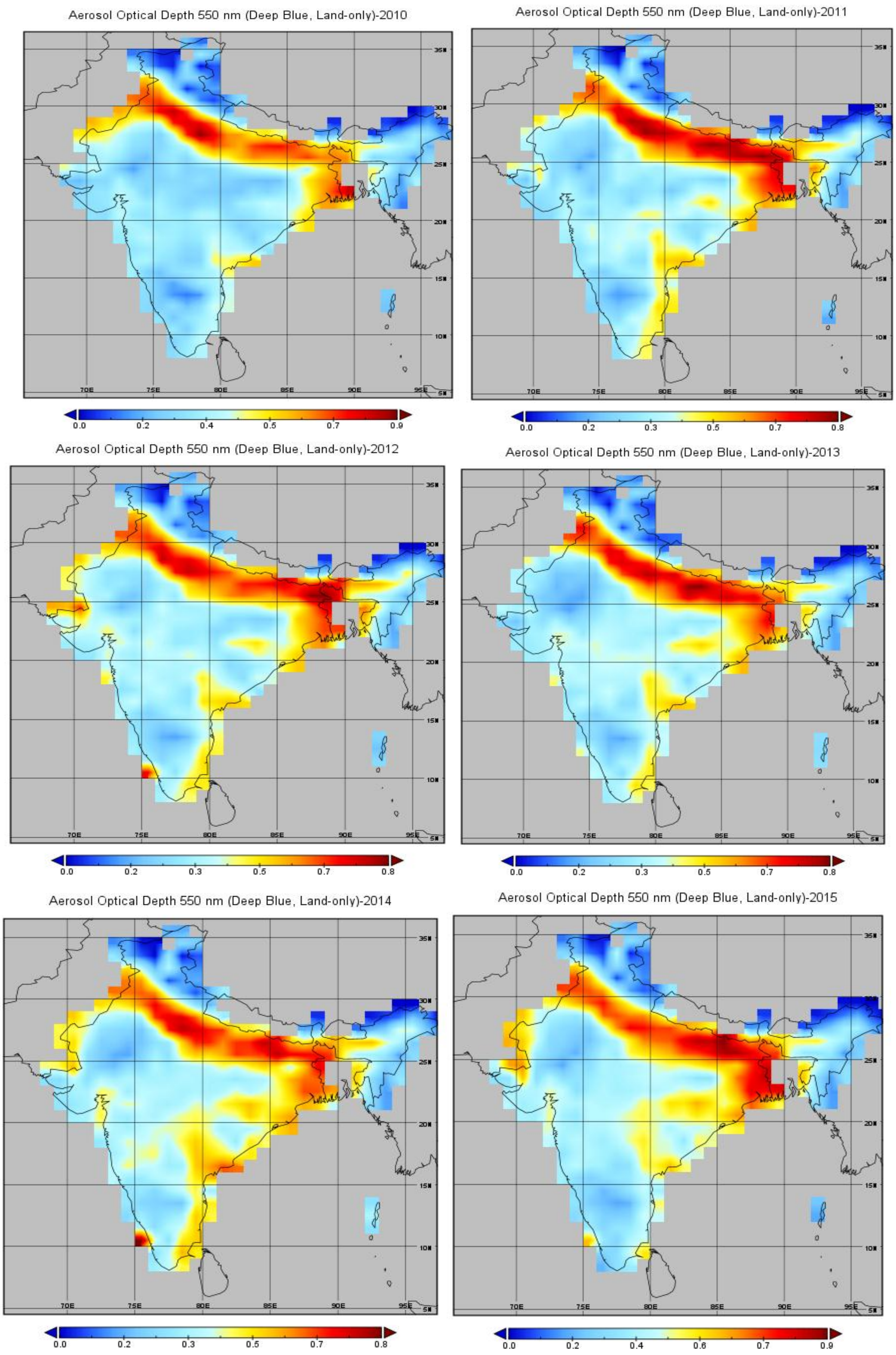

Figure 3: MODIS Terra monthly AOD variations over major Indian cities from 2015 to 2020

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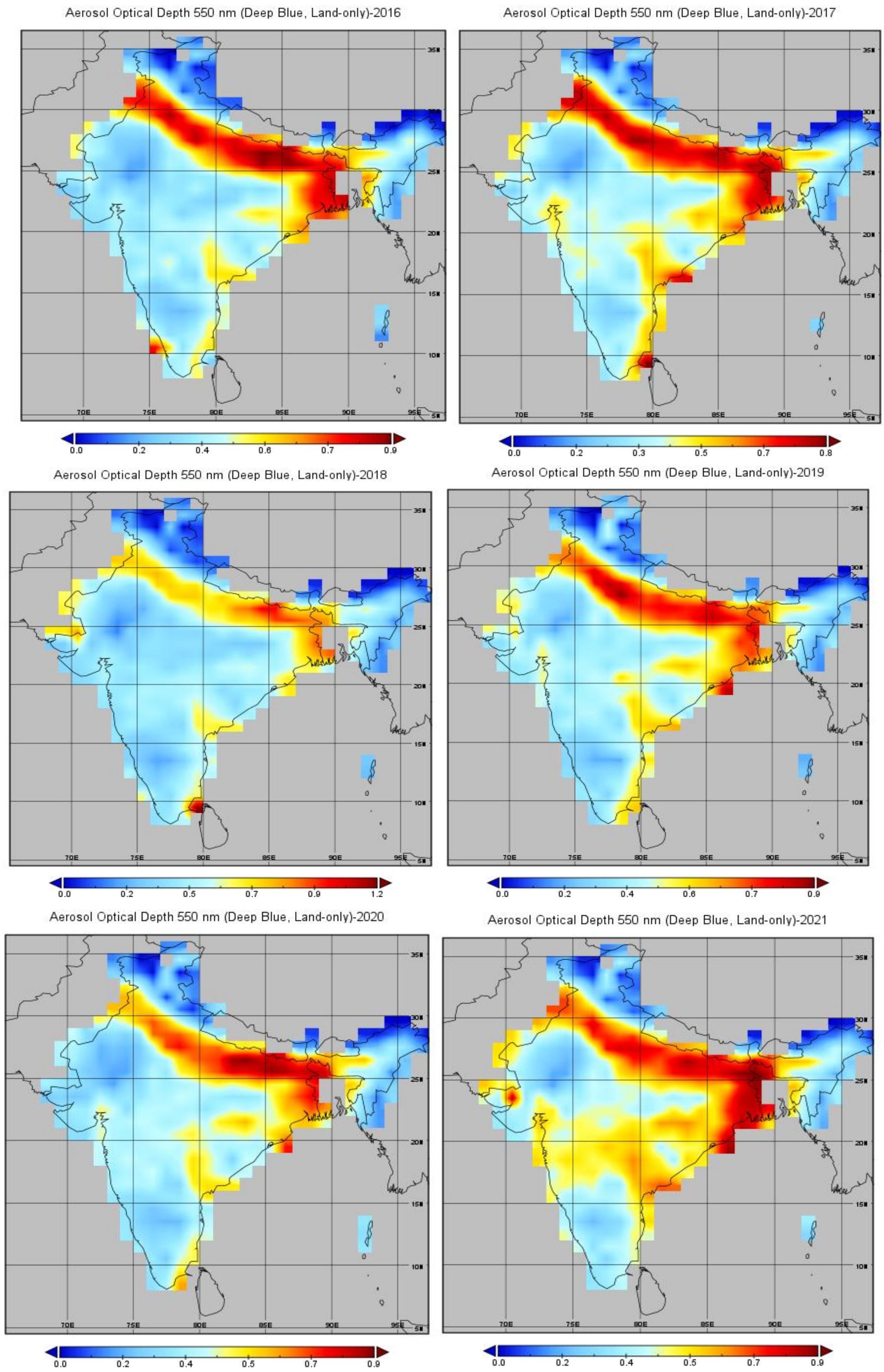

Figure 4: MODIS Terra annual AOD variations over major Indian cities

These noticeable rising trends, which are practically ubiquitous throughout India, are equally attributed to either natural or anthropogenic factors or a combined effect.

Analysis of seasonal mean variations in AOD

AOD retrieved from MODIS Terra satellite sensor for spatial variation from 2010 to 2021 over five major Indian regions (as shown in Figure 1 and Table 3 Kolkata, Mumbai, Jaipur, Surat, and Ahmedabad). As depicted in Figure 5, all the selected Indian cities show higher AOD concentrations during the winter and monsoon period (0 to 1.2). Dust activities affected by moisture in the soil, wind speed, rainfall, and monsoon onset result in an increase in AOD in the pre-monsoon season that peaks in the monsoon season [29]. Kolkata shows high AOD concentration during (0.7-1.1) winter and monsoon, caused by stable weather and localized burning (stove used for cocking and vehicular emission), whereas mean AOD is 0.6-0.8 in pre-monsoon and post-monsoon. It has been observed that aerosol accumulation increased over IGP (Indo Gangetic Plan) from west to east, which may be related to wind and a stable environment. Jaipur has significant aerosol loading (0.3-0.4) during the pre-monsoon as well as monsoon seasons.

It is probably caused by desert dust, hygroscopic accumulation of aerosol particles, and heavy winds from the southwest, respectively. However, during the post-monsoon period, low AOD values (0.10-0.25) indicate the probability of wet deposition. Due to the blowing of crop residues by northwesterly winds originating across Punjab and Haryana during the post-monsoon, an average AOD value (0.85-0.95) is observed at [30,31]. Both coastal regions, Surat and Mumbai, show moderate change during the whole season, except in post-monsoon, which shows slightly higher AOD values than other seasons. Higher AOD value is observed in Ahmedabad during Monsoon and post-monsoon.

Analysis of monthly mean variations in AOD

The AOD also varies significantly from month to month, as depicted in the radar plot in Figure 6 and Table 4. Figure 5 shows AOD variation over selected regions. AOD levels increase from the center to the perimeter, and ring size increases as AOD increases for different cities. The improved cloud screening algorithm of MODIS AOD retrieval procedure [11,32] shows data gaps around the monsoon months (June to September). Surat showed the highest AOD value (0.9) in June 2021, whereas the lowest AOD value (0.2) was observed in May 2020 and in general (0.4). Due to the humid climate of the coastal city of Surat AOD of this city was lower than other regions. The mean AOD concentration in Mumbai was the minimum (0.1), while the maximum (0.88) was found during September and November, respectively. The relatively lowest mean AOD over Kolkata was found to be 0.1 during August, while the highest AOD found to be 1.6 during February. The mean AOD concentration in Ahmedabad was found to be a minimum (0.2) during most of the months, while the maximum value was found during July (1.0). In Jaipur, the AOD value was the minimum (0.1-.02) throughout the year while the maximum (0.8) was observed during November. The dust aerosol particles are the primary reason for the variability in Jaipur [17].

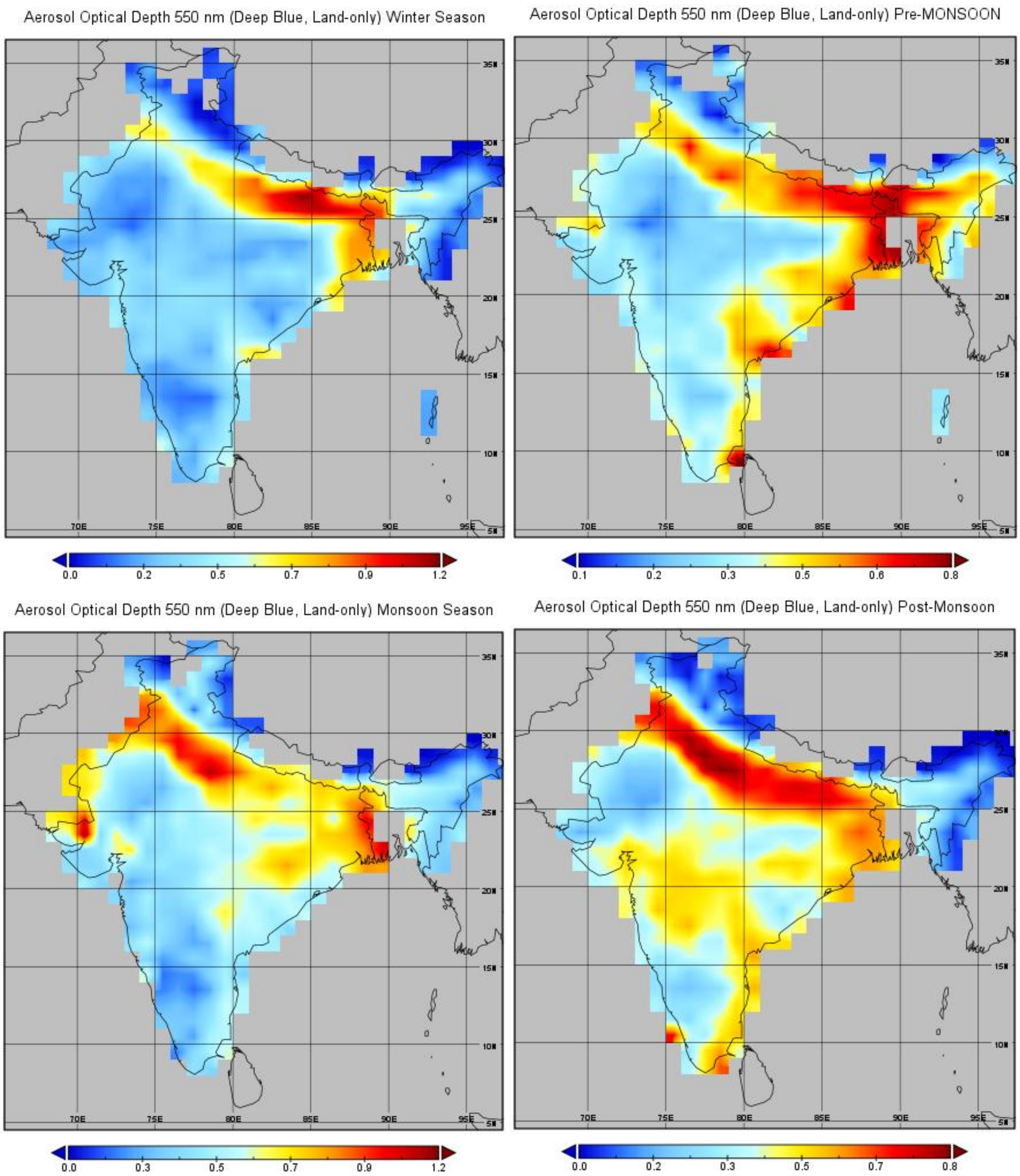

Figure 5: Spatial AOD distribution for seasonal MODIS Terra over major Indian cities

Table 3: Seasonal average and STD

Months	KLK		MUM		ST		AHM		JAI	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
Winter	0.84	0.26	0.43	0.10	0.45	0.13	0.43	0.13	0.24	0.09
Pre-monsoon	0.72	0.21	0.39	0.06	0.36	0.07	0.36	0.06	0.21	0.07
Monsoon	0.71	0.25	0.41	0.15	0.56	0.17	0.60	0.17	0.22	0.12
Post-monsson	0.59	0.14	0.46	0.12	0.51	0.10	0.50	0.10	0.30	0.17

*Avg: Average
**Std: Standard Deviation

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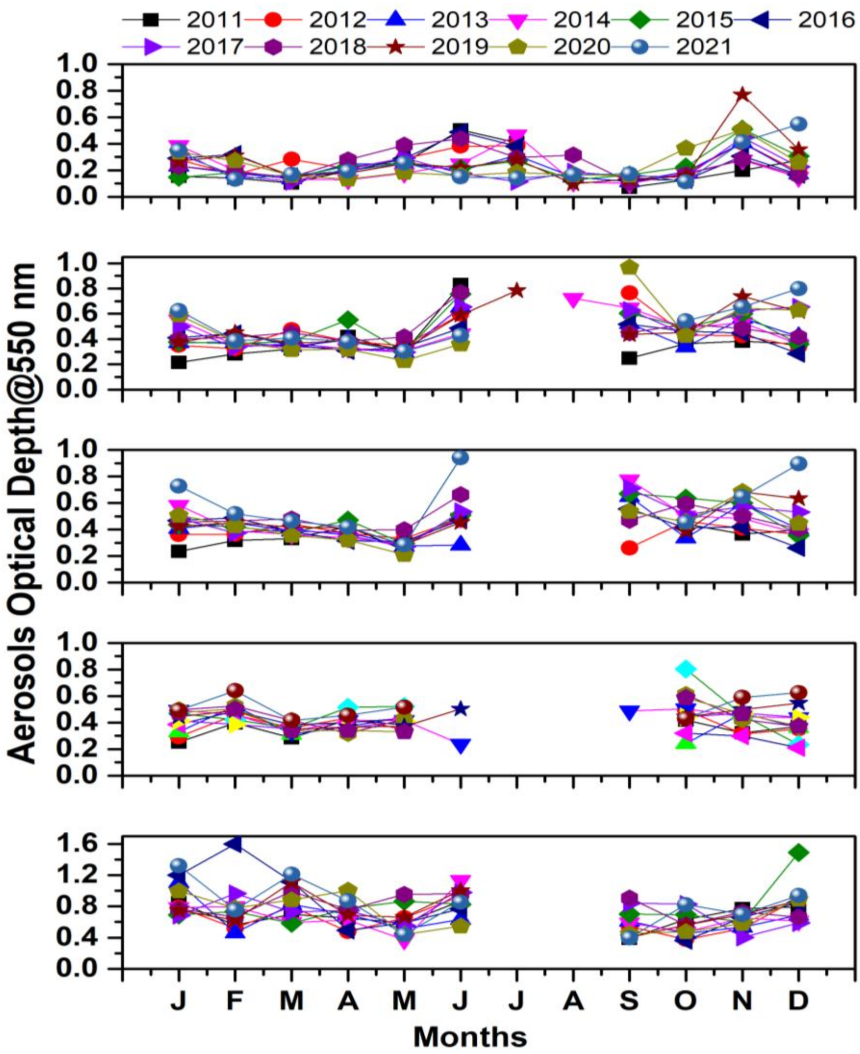

Figure 6: AOD product derived from MODIS Terra over the Indian regions (Kolkata, Mumbai, Ahmedabad, Surat, and Jaipur) during 2010-2021

Table 4: Monthly trend in the study cities

Months	KLK	MUM	ST	AHM	JAI
Jan	0.90	0.41	0.46	0.43	0.27
Feb	0.77	0.48	0.42	0.37	0.20
Mar	0.87	0.35	0.40	0.37	0.15
Apr	0.71	0.40	0.38	0.38	0.20
May	0.60	0.42	0.29	0.31	0.26
Jun	0.86	0.37	0.54	0.60	0.29
Jul	ND	ND	ND	0.78	0.29
Aug	0.19	ND	ND	0.72	0.16
Sep	0.58	0.49	0.58	0.58	0.13
Oct	0.57	0.48	0.47	0.45	0.18
Nov	0.62	0.43	0.54	0.55	0.41
Dec	0.84	0.39	0.46	0.48	0.25

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Higher values in these months showed the cloud contamination in observed MODIS AOD values. Figure 6 shows the variation of MODIS Terra monthly mean values in Kolkata, Mumbai, Ahmedabad, Surat, and Jaipur. The improved cloud screening algorithm of MODIS AOD retrieval procedure [11,32] shows data gaps around the monsoon months (June to September). Lower AOD values were mostly observed in May for all the years and locations (Kolkata, Mumbai, Surat, Jaipur, and Ahmedabad). An overall decreasing annual tendency was observed in Surat and Ahmedabad, whereas increasing trends were observed in Kolkata and Mumbai. The variability peaks were observed from May to June. The data from July to August were not considered due to considerable uncertainty during these periods.

During the study period, we observed that Kolkata showed the mean AOD value 0.8 ± 0.2, except for December 2015 and January 2016, 2017, 2019, and 2020 which showed uncertainty (Figure 6). Mumbai also showed a mean value of 0.6 ± 0.2, except for October 2020. The mean AOD value was 0.6 ± 0.3, except for September 2017. Jaipur showed a mean value of 0.4 ± 0.2, except for November. Ahmedabad also showed a mean value of 0.4 ± 0.2 throughout the year except in July 2019, as shown in Figure 6.

Trends in AOD at four locations

AOD tendencies were calculated by taking the difference of annual average AOD for twelve years (January 2011 to December 2021) depicted in Figure 7 in five locations (Kolkata, Mumbai, Surat, Jaipur, and Ahmedabad). It is found that overall decreasing linear tendencies and trends were found in all periods. Kolkata showed higher annual average AOD values (0.72 ± 0.23), while Jaipur showed lower annual average AOD (0.23 ± 0.11). The mean AOD values in Mumbai, Surat, and Ahmedabad were 0.41 ± 0.09, 0.44 ± 0.13, and 0.39 ± 0.14, respectively, indicating moderate AOD values during the study period.

MODIS Terra sensors could be due to decreasing anthropogenic activities depending on the population and area of the location.

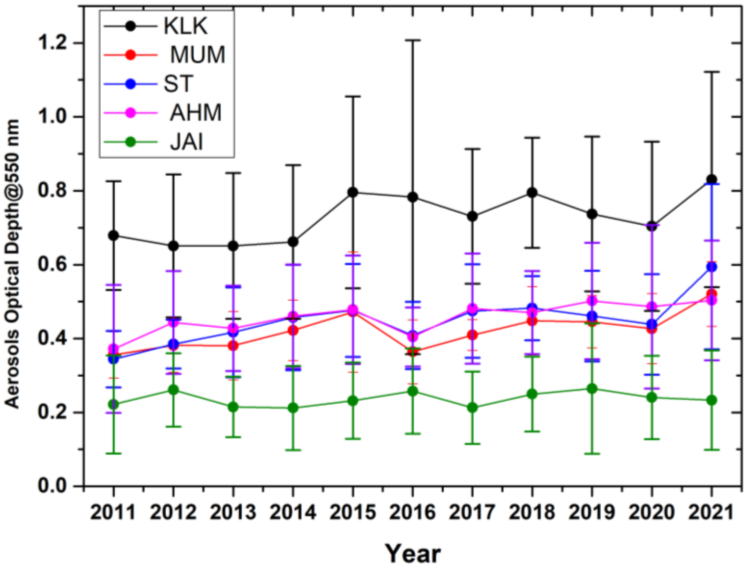

Figure 7: Line plot for Terra mean cumulative AOD trends during twelve years (January 2010 to December 2021) in Jaipur (JAI), Mumbai (MUM), Kolkata (KLK), Surat (ST), and Ahmedabad (AHM)

Effect of meteorological parameters along with AOD values in the study regions

Previous studies have noted that meteorological factors, such as wind speed, temperature, and relative humidity, has a strong impact on AOD [33,34]. Figure 8 shows the meteorological parameters of temperature (°C), and relative humidity (%) obtained from NASA'S MERRA-II platform at 2 m from sea level along with AOD for the 12 years (2010-2021). Lower AOD values were observed in Jaipur, Ahmedabad, and Mumbai by increasing temperature. Figure 8 reveals the inverse relationship between these parameters for Jaipur, Ahmedabad, and Mumbai during the 12 years (2010-2021).

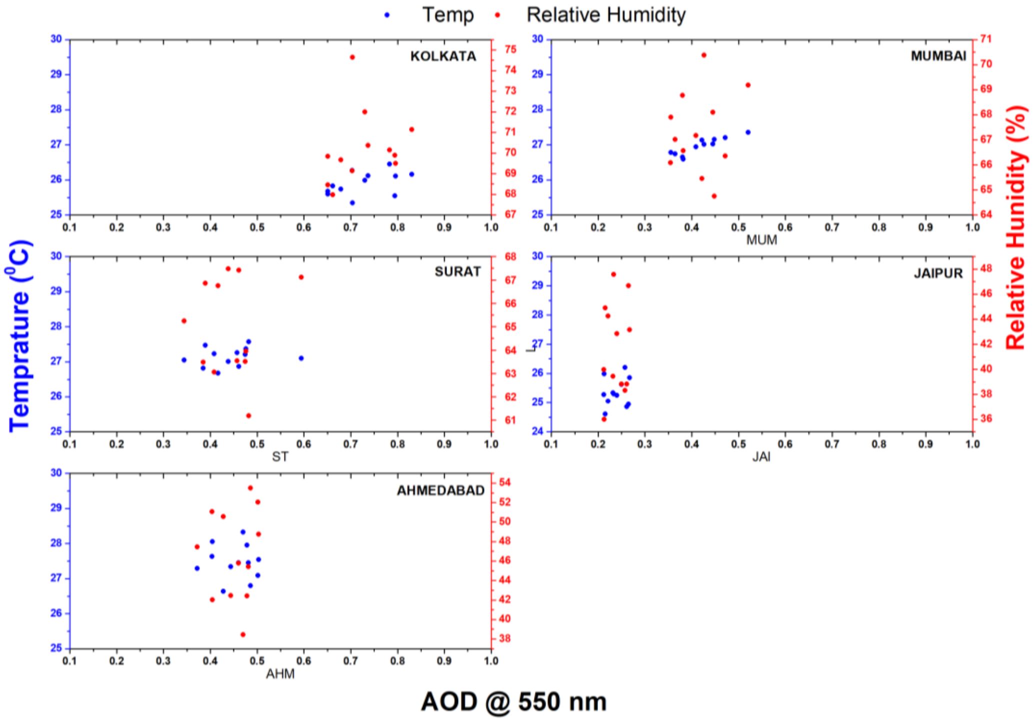

Figure 8: Impact of meteorological parameters along AOD in Jaipur, Ahmedabad, Surat, Mumbai, and Kolkata during 2010-2021

Overall, based on the results, Kolkata's highest value was seen (0.8) during 2021, and the lowest value was ~0.2 for most of the years. There were relatively moderate variations in Mumbai, Ahmedabad, and Surat throughout the study period.

As shown in Figure 8, Ahmedabad and Jaipur are semi-arid regions; therefore, they showed lower humidity levels of 53% and 47% during 2020 and 2021, respectively. Due to the fact that Kolkata, Mumbai, and Surat are coastal areas, higher relative humidity levels of 74%, 70%, and 67% were observed, respectively.

Discussion

The major findings of the study are as follows:

- Significant changes were observed during the study period over the Indian cities from the previous year to the recent year. The Eastern region of Kolkata showed higher AOD concentration compared to the western areas, including Mumbai, Ahmedabad, Surat, and Jaipur. This is due to the fact that IGB has high industrial development and population growth, and Himalaya Mountains' presence is the main factor in increasing the level of AOD in the region.
- The seasonal variation shows the maximum AOD during winter and monsoon (0.1 to 1.2), while during pre-monsoon and post-monsoon lower values were observed. Kolkata shows the maximum AOD (0.8) during winter and monsoon. Low to moderate AOD values were observed in Mumbai, Ahmedabad, Surat, and Jaipur. Kolkata showed higher AOD values for all the seasons compared to other regions.
- In contrast, Jaipur, Ahmedabad, Surat, and Mumbai reported lower mean AOD values with STD than Kolkata, which were (0.23 ± 0.11), (0.45

± 0.14), (0.44 ± 0.13), (0.41 ± 0.09), and (0.70 ± 0.09), respectively.

- Regarding meteorological parameters along with AOD, higher temperatures with lower AOD values were found except in Kolkata and Surat. However, the relative humidity level was lower compared to other regions. A reverse trend was observed for Jaipur, Ahmedabad, and Mumbai, with lower AOD and higher temperature and relative humidity, except for Ahmedabad, which reported lower relative humidity.

Conclusion

The selected Indian regions are of great interest for AOD studies, due to their topography and industrial growth, as well as highly growing cities in India. This study examined AOD spatial and temporal distribution over five major Indian cities. The study primarily observed annual, seasonal and monthly distribution, and the monthly mean AOD value was obtained at 550 nm from January 2010 to December 2021 from the MODIS instrument on the Terra satellite.

Acknowledgment

The authors are thankful to the MODIS team and NASA (https://giovanni.gsfc.nasa.gov/giovanni/) for providing satellite data and to NASA Goddard Earth Sciences Data and Information Services Center MERRA-II (https://www.soda- pro.com/ web-services/meteo-data/merra) for providing meteorological data.

Funding

None

Conflict of interest

The authors declare that there is no conflict of interest.

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