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(Research Article)

# Aerosol optical depth variations in Delhi and Lucknow over a period of 10-year (2013-2022)

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## Abstract

This research paper focuses upon descriptive analysis of the variation in Aerosol Optical Depth (AOD) over a duration of ten years (from 01-01-2013 to 01-01-2023) for Delhi and Lucknow cities. Higher values were found throughout the winter and lower values were found during the monsoon season in both cities, according to a study of monthly AOD data. Compared to Delhi, Lucknow typically had slightly higher AOD readings, with noticeable variability in certain months. We found that for Lucknow the AOD levels ranges from 0.55 in March to 1.07 in January, on the other hand for Delhi the AOD values ranges from 0.60 in March to 0.96 in June. Seasonal study revealed differing trends, with Delhi's AOD levels being higher in the summer but somewhat equivalent to those of the winter, with the exception of the winter of 2019 when AOD exceeded one. AOD readings in Lucknow were typically higher in the winter, however there have been some instances in the summer and autumn of 2018 and 2019 when they were higher than average. Complementing these findings, a statistical analysis using the t-test method was also carried out which suggests that when considering the overall period under study, there wasn't a substantial difference in air quality between Delhi and Lucknow. Our study points out what is the importance of understanding the patterns of aerosol in both the cities (i.e., Delhi and Lucknow) in order to evaluate the air quality and might be helpful in mitigating negative environmental effects of aerosols. It also provides valuable information on the geographical and temporal variability of AOD.

**Keywords:** Aerosol optical depth; Temporal variation; Lucknow; Delhi; T-test

## 1. Introduction

Aerosols, present in atmosphere play a major role as air pollutants, and their presence can lead to various climatological shifts and health consequences [1]. During wintertime and spring, dense haze and dust storms have had a significant impact on millions of individuals in the South Asian region [2, 3]. High concentrations of air pollutants, such as aerosols, are linked to a number of diseases, such as cancer of lung, respiratory diseases, and cardiovascular issues [4, 5]. Additionally, atmospheric aerosols can influence the radiative budget of the Earth [6, 7].

In contrast, AOD quantifies the cumulative presence of diverse aerosols, encompassing urban pollution, smoke particles, desert dust, and sea salt, dispersed throughout an atmospheric column. It estimates the amount of light which is prevented to travel from surface of the Earth to the top of the atmosphere as a result of aerosols. The level of haze or dust particles in the air, from the ground up to the sky, is commonly measured to understand its effects. This measurement, known as AOD, is a useful way to study how tiny airborne particles (aerosols) affect our environment [8].

AOD readings can be used to infer that high $PM_{2.5}$ concentrations are frequently accompanied by high aerosol concentrations. With rising $PM_{2.5}$ levels, India has become known as one of the world's pollution hotspots in recent years [9]. 37 Indian cities have been listed amongst the 100 cities having the highest levels of $PM_{2.5}$ worldwide, based on a new study published by the World Health Organization (WHO) (WHO, 2016). Notably, the Indo-Gangetic Basin (IGB) in

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north India's Kanpur, Faridabad, Delhi, and Lucknow are ranked among the top 10 cities with the worst $PM_{2.5}$ levels [10].

The IGB contains about 1/7th of the total population of the world, comes under the regions with the highest amounts of elevated aerosol loading. These aerosols frequently exhibit distinct seasonal patterns and are composed of a diversity of anthropogenetic and natural emissions [11, 12, 13, 14, 15, 16]. Therefore, affecting AOD levels.

In the earlier twenty years, several researches have focused on examining the distribution, optical characteristics, and transportation of aerosols in certain regions of the South Asia, mainly the IGB, using both model techniques and explanations [17, 18, 19, 20].

There are two AOD measuring instruments namely ground sun photometers and satellite sensors. Both can be used to monitor AOD, giving complementary techniques for complete AOD measurements [21].

Satellite observations have been very helpful in developing a number of models to calculate AOD. Though, the models are influenced by the quality of AOD product recoveries and uncertainties associated with other factors [22, 23, 24, 25].

The major portion of the air pollution associated studies have primarily concentrated to Delhi, the nation's capital, along with several other major cities in India [26, 27, 28]. But there are very limited research works was carried to determine AOD levels in Lucknow city. During the research conducted for Lucknow city, it was found that the AOD exhibited significant variations during the past 20 years. The month of January recorded the highest percentage increase in AOD, showing a substantial rise of 86.5% [29].

There are few thorough studies comparing AOD variations between Lucknow and Delhi, despite the fact that there has been a lot of research on the patterns of air quality in Delhi. A full time series analysis of AOD levels in both cities over a 10-year period will therefore be conducted as part of this study. This research work uses the data from NASA's Giovanni (MODIS Terra satellite) to determine the time-based differences of AOD and plotting it for both the cities.

The aim of this study is to be proven useful in understanding unique characteristics of aerosol loading in Delhi and Lucknow cities, providing valuable insights for policymakers and environmental authorities. Based on these observations, effective air quality management plans can be created with the goal of reducing aerosol pollution and improving the air quality in the center of IGB, promoting healthier and more sustainable urban environments in Delhi and Lucknow.

## 2. Material and methods

### 2.1. Description and meteorology of the studied area

This research concentrates on two urban cities namely Lucknow and Delhi, both the them are located in the IGB and having a climate type known as semi-arid climate. The motive of the study based upon examining the variation in the AOD and aerosol properties in these highly populated and urban locations. We know that both cities experience extreme climate with summer temperatures reaching approximately 45 °C and chilling winter season with temperature dropping as low as 3 °C.

Lucknow is positioned in the central IGB in north of the India. It has a latitude of 26.8°N, longitude of 80.9°E and an elevation of 128 meters above the mean of sea level. On the other hand, Delhi is sited in the north-west side of the IGB with a latitude of 28.4°N and longitude of 77.1°E with an elevation around 215 meters above mean sea level. More about selected area is discussed below:

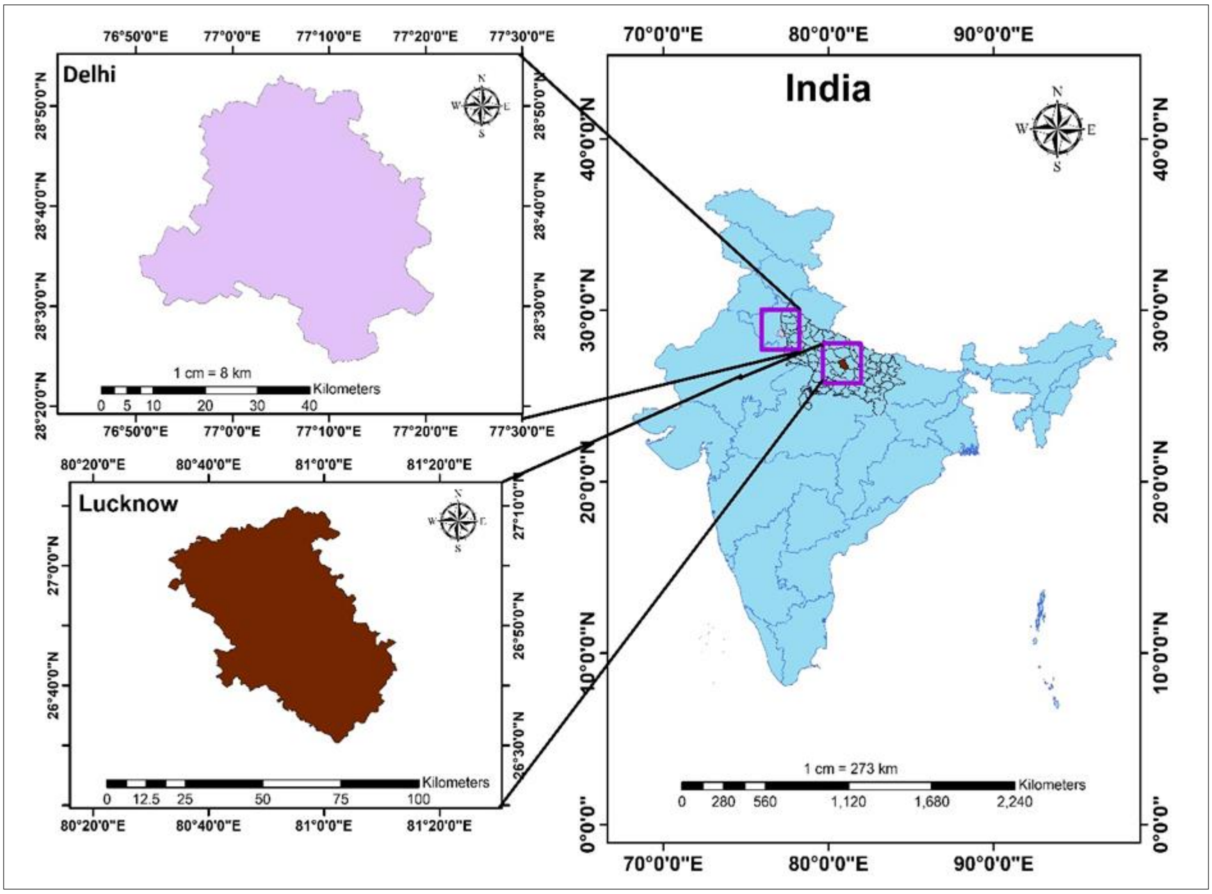


**Figure 1** Area location map of Delhi and Lucknow cities within India

*2.1.1. Delhi*

Delhi, positioned in the south of the Aravali range, is a densely populated city with approximately 1.7 crores people as per the Census of 2011. It spans an area of around 1500 km$^2$. The city is surrounded by the Yamuna River in the east, the central Indian plains in the south, and the Desert of Thar in the west. Within the vicinity of Delhi, numerous small and medium-scale industries coexist, contributing to its pollution levels. Moreover, the city is home to around 70 lakhs recorded vehicles, which serves as the primary sources of air contamination in the area.

Both Lucknow and Delhi are part of the heavily polluted and densely populated IGB, situated in the north zone of India. This vast region is a significant agricultural center for India and Pakistan due to its proximity to the Indus River, resulting in a substantial population load driven by urbanization and various anthropogenic activities, leading to increased emissions.

The exclusive geography of the IGB, bounded through the Himalayan ranges to the north, contributes to detention of varied aerosols in the entire region. This confinement increases the air pollution levels in the area.

*2.1.2. Lucknow*

This urban center, situated at the shore of the river named Gomati, has exhibited remarkable expansion over time, with its area increasing from 143 km$^2$ in 2001 to 310 km$^2$ in 2011. The population has also witnessed significant growth, estimated at around 22 lakhs in 2001 and reaching approximately 28 lakhs in 2011 according to Census data.

An analysis of the sources contributing to an overall air pollution in the city of Lucknow reveals that vehicular emissions, along with the dust, which blows with wind due to vehicular activity and ongoing metro building, are identified as the primary contributors (Kumar et al., 2021).

### 2.2. Data collection

In following study, daily information for Aerosol Optical Depth 550 nm (Deep Blue, Land-only) at 1-degree resolution for a period of 10 years (from 01-01-2013 to 01-01-2023) for both the cities was obtained from the MODIS Terra platform, specifically using the dataset labelled [MODIS-Terra MYD08_D3 v6.1]. The data retrieval was conducted through NASA's GIOVANNI site.

MODIS, which stands for Moderate Resolution Imaging Spectroradiometer, is a crucial satellite device within NASA's Earth Observing System (EOS). It was launched aboard the Terra satellite in December 1999 and the Aqua satellite in May 2002. Depending on the particular spectral band, it provides data at a variety of spatial resolutions, ranging from 250 metres to 1 km. Researchers are able to accurately and thoroughly explore several Earth-related elements owing to this wide range of resolutions.

Additionally, the public can freely view and download MODIS data from a number of data portals, including NASA's Earth Observing System Data and Information System (EOSDIS). The easily accessible figures promote transparency as a result the scientific community is also encouraged to use it for a variety of studies and applications.

### 2.3. Methodology

In this paper, we divided the study in descriptive and statistical analysis. Therefore, for the descriptive analysis we plot the temporal variations of AOD for both the cities (i.e., Lucknow and Delhi) based upon our data of past 10 years using python on google collab platform and perform the comparison. We carried out our analysis as described in the flow Fig.2 below.

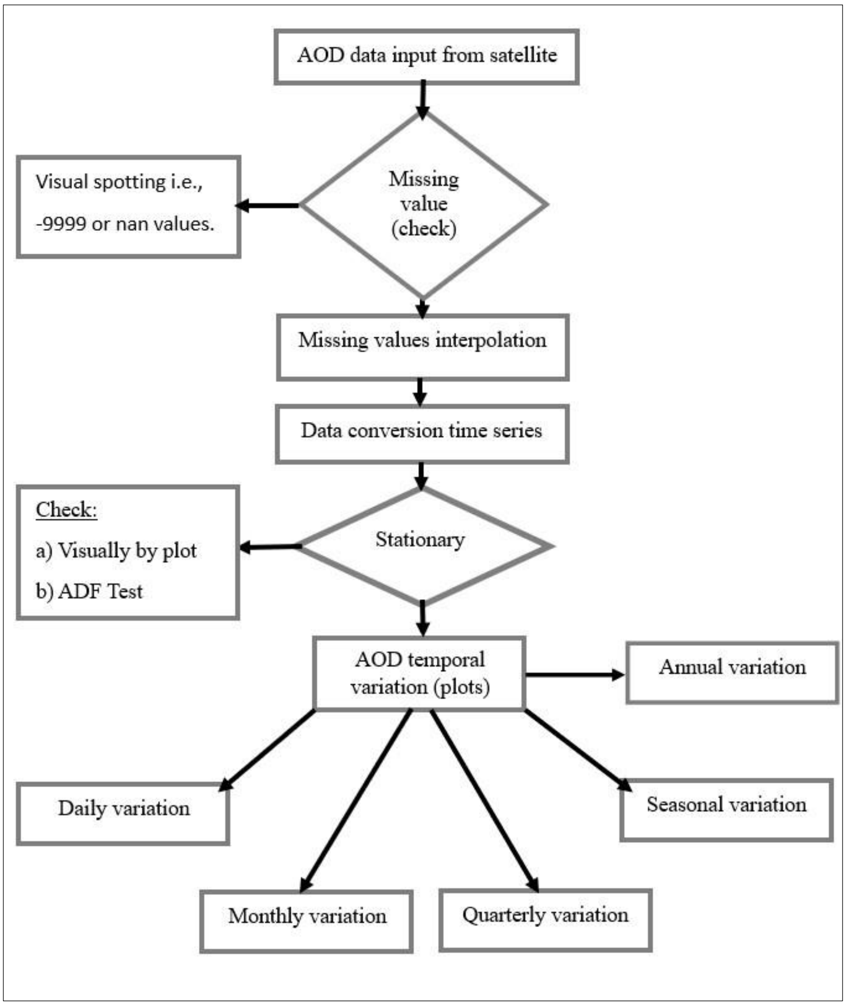


**Figure 2** Flow chart of descriptive investigation of AOD Variations for Delhi and Lucknow over a 10-Year Period

Initially, we checked for missing values in AOD data and found many by inspection so we carried out forward and backward interpolation to fill those missing values. Usually, the missing values are dropped in python but since data had so many missing values, so interpolation method was chosen for better results.

To check whether the AOD data is stationary we did visual inspection and also ADF (Augmented Dickey-Fuller) test is conducted using python to identify drifts and outlines in the data for time series examination. It is a statistical method used to determine the stationarity of a time series data, examining whether it possesses a unit root (non-stationary) or not.

We imported 'pandas' library for data manipulation and then converted 'time' column to datetime format to work with the dates. Then we assigned each data point to a season based on the month in the 'time' column using custom-defined month ranges. After that we calculated mean of AOD values for each unit of time (e.g., monthly, quarterly, or seasonally) by assigning appropriate time units to them. To visualize the results in bar diagram format we used 'matplotlib.pyplot' library. Finally, we plotted the temporal variations of AOD using 'plt.show()' for both the cities (i.e., Lucknow and Delhi) on our data of past 10 years using python on google collab platform and compared it.

For the statistical analysis, in order to make the task easier we used the monthly data instead of daily data from same platform and performed a t-test using python. To perform the t-test, we used the SciPy.stats library in Python. The t-test calculates a t-statistic, which quantifies the difference between the means of the two groups, and a p-value, that denotes the possibility of finding such difference by random chance, presumptuous that the null hypothesis is correct. Scipy, which is a SciPy sub-package and mostly used in statistical operations and probabilistic operations. The primary objective of the t-test is to check whether there is a noteworthy alteration amongst the mean of AOD standards of both the cities. The analysis is done at 0.05 significance level and 95% confidence level. It tests for the following hypothesis:

- Null Hypothesis ($H_0$): There is no significant difference between the means of 'Delhi AOD data' and 'Lucknow AOD data'
- Alternative Hypothesis (Ha): There is a significant difference between the means of 'Delhi AOD data' and 'Lucknow AOD data'

The choice of a 95% confidence level and an alpha level of 0.05 is a common practice in hypothesis testing, providing a standard threshold for determining statistical significance.

## 3. Results and discussion

### 3.1. Augmented Dickey-Fuller (ADF) Test

Since we utilized Python's ADF test to see whether the data for both cities is stationary or not, we obtained the figures shown below:

**Table 1** P-values and their significance level obtained utilizing ADF-test

| Sl. No. | City name | P-values | Significance level |
|---|---|---|---|
| 1. | Delhi | 1.639e-13 | 0.05 |
| 2. | Lucknow | 2.601e-12 | 0.05 |

Strong evidence is presented in contradiction of the null hypothesis of non-stationarity by two exceptionally low p-values. The null hypothesis could be rejected because both p-values are considerably lower than usual significance level of 0.05, which allows us to draw the conclusion that the data is stationary.

### 3.2. Temporal Variations

Daily variation of AOD data for 10 years (01-01-2013 to 01-01-2023) is plotted for both the cities using excel. Similarly, other temporal variations for AOD data are plotted but in bar diagram format using python (i.e., for Delhi on left hand side and for Lucknow on right hand side).

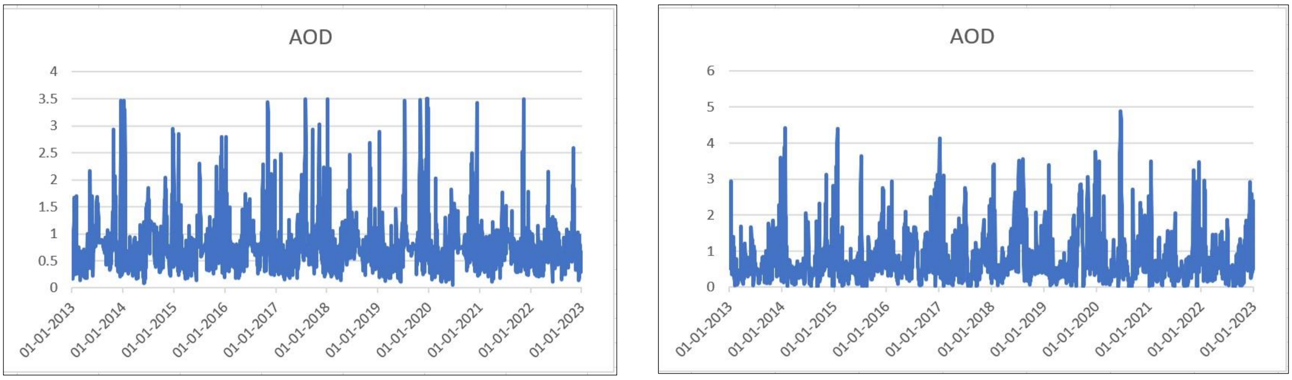


**Figure 3** Daily AOD variation in cities Delhi (on left side) and Lucknow (on right side)

Over the course of ten years, the average monthly Aerosol Optical Depth (AOD) data for Delhi and Lucknow reveal interesting variances between the two cities. Both cities have AOD readings that are smaller in the monsoon and greater in the winter season. But generally speaking, Lucknow displays slightly higher AOD readings than Delhi, with noticeable variations seen in particular months.

For Delhi, the AOD values lies in between 0.60 in March to 0.96 in June, with the highest value recorded in June. On the other hand, Lucknow experiences AOD values ranging from 0.55 in March to 1.07 in January, with the highest value occurring in January. Apart from January, Lucknow also shows higher AOD values in August and December compared to Delhi. The existence of several elements, such as local emissions, physical qualities, and climatic conditions that are unique to each city, could account for the variations in AOD values among both towns.

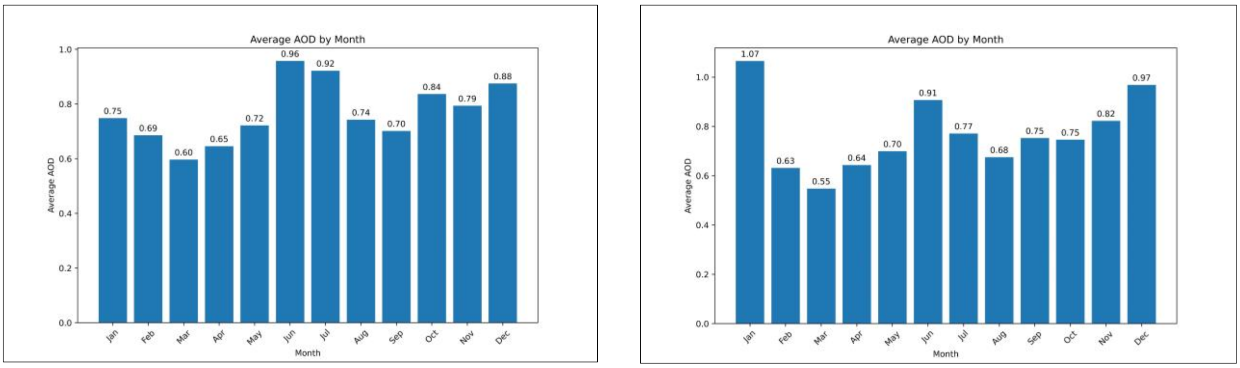


**Figure 4** AOD variation (monthly) between the cities of Lucknow (on the right) and Delhi (on the left)

The ten years (2013–2023) quarterly AOD variation for Delhi and Lucknow offers important information about the atmosphere aerosol levels in these two cities. The quarterly AOD values are divided into quarter 1 i.e. (Q1) January to March, quarter 2 i.e. (Q2) April to June, quarter 3 i.e. (Q3) July to September, and quarter 4 i.e. (Q4) October to December.

AOD readings in Delhi gradually rise from the first to the fourth quarters, with values of 0.68, 0.77, 0.79, and 0.84, respectively. This pattern indicates that aerosol loading increases gradually over the course of the year, possibly affected by a variety of seasonal causes and greater anthropogenic activity in the second half of the year.

On the other hand, Lucknow displays a somewhat similar trend, with respective quarterly AOD values of 0.75, 0.75, 0.73, and 0.85. However, overall AOD values in Lucknow are slightly higher compared to Delhi for most quarters, indicating a relatively higher aerosol burden throughout the year in this city.

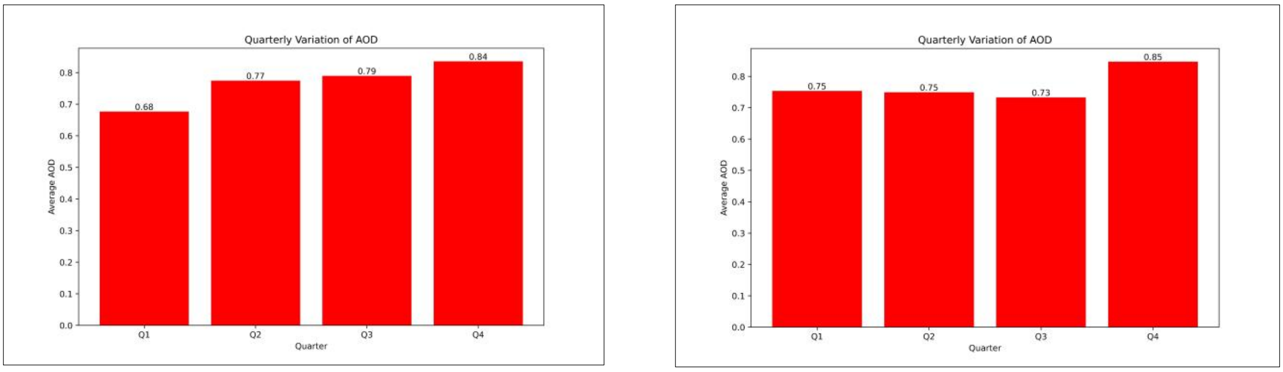


**Figure 5** Quarterly AOD variation in cities Delhi (on left side) and Lucknow (on right side)

The analysis of seasonal AOD variation for Delhi and Lucknow reveals distinct seasonal patterns in these cities. Four seasons namely autumn, spring, summer, and winter which are considered for this investigation.

In Delhi, the AOD values generally show higher levels during the summer months, but they are closely comparable to the winter months in each year, except for the winter of 2019 when the AOD surpassed a value of 1. This suggests that summer months consistently have higher aerosol loading, which could be attributed to variables such as higher temperatures, increased industrial activity, and regional climate patterns that favor aerosol formation. However, the significant spike in AOD during the winter of 2019 may have been influenced by specific meteorological conditions and an upswing in pollution sources during that particular period.

Conversely, Lucknow exhibits a different seasonal trend, with AOD values typically being highest during the winter months in most years. However, there are two notable exceptions: in the summer of 2018, the AOD reaches 1.75, exceeding the winter values, and in the autumn of 2019, it reaches 1.50, also higher than the winter values. These variations in AOD might be credited to localized features like specific releases sources, unique meteorological conditions, and fluctuations in industrial and vehicular activities during these particular periods.

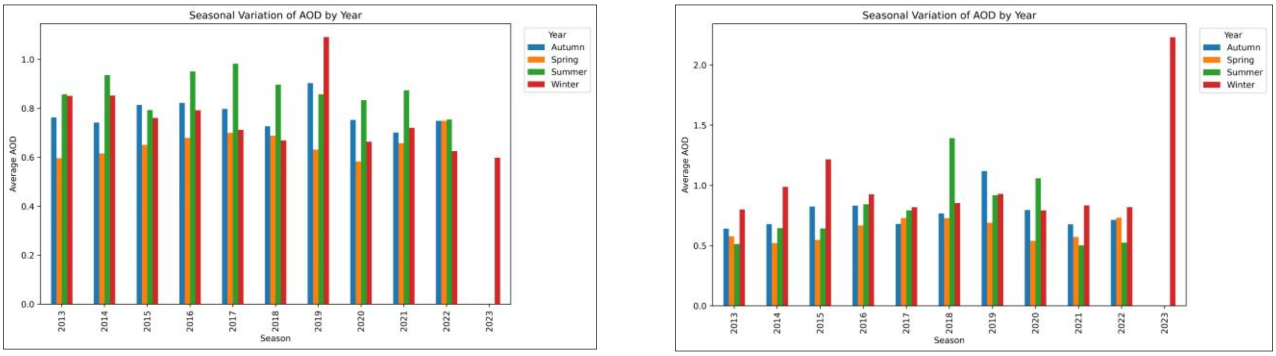


**Figure 6** Seasonal AOD variation in cities Delhi (on left side) and Lucknow (on right side)

In the period of 2013 to 2023, both Delhi and Lucknow witnessed fluctuations in their annual AOD values. Delhi generally exhibited slightly higher AOD values, peaking at 0.87, while Lucknow reached its highest at 0.94 in 2016-2017. However, in 2023, Delhi's AOD declined to 0.6, contrasting with Lucknow's highest value. These variations result from environmental factors, weather, and local activities, showcasing the dynamic nature of air quality, with implications for public health and policy.

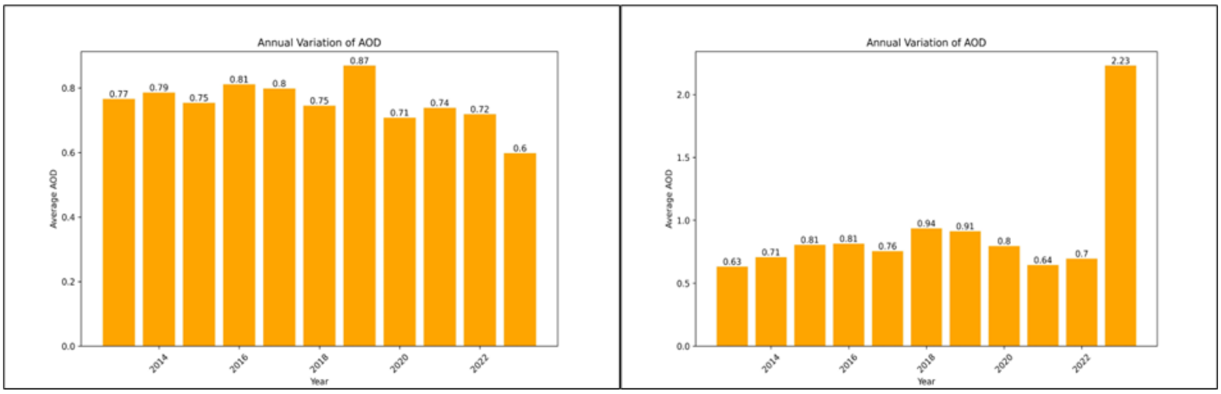


**Figure 7** Annual (average) AOD variation in cities Delhi (on left side) and Lucknow (on right side)

### 3.3. Statistical test

We carried out a T-test to check for any significant difference between the AOD values of both the cities (i.e., Lucknow and Delhi), the following results are obtained:

We assumed: Significance level (alpha) = 0.05

T-statistic = 1.31672

P-value = 0.17456

Since P-value > Significance level we can say it failed to reject null hypothesis ($H_0$) i.e., There is no significant difference between the means of 'Delhi AOD data' and 'Lucknow AOD data'.

## 4. Conclusion

In brief we can say that our research work performed a complete analysis of 10 years AOD data for Delhi and Lucknow cities. It is found that the monsoon season had lower AOD values than the winter for both the cities based on our study, which also identified distinct seasonal variations in AOD levels. Notably, Lucknow generally exhibited slightly higher AOD readings compared to Delhi, with some variations in specific months. The key finding of the study suggests in spite of these variations, a complete statistical analysis which was conducted utilizing the t-test turned out to be failure to detect a statistically significant difference between the average AOD values of the two cities. This shows when evaluating air quality how important is to take into account the averages and long-term trends.

This study provides the valuable insights related to spatial and temporal AOD variations which helps us in understanding the aerosol behavior and dynamics in urban environments. The results obtain can significantly contribute in development of strategies related to air quality challenges and its improvement. Therefore, this research has potential to inform policymakers in creating guidelines and practices aiming to create cleaner and healthier urban environment worldwide.

## Compliance with ethical standards

*Acknowledgments*

I present my gratitude towards Civil Engineering Department, IET Lucknow for constant support and advice during my research on AOD and its variations in Delhi and Lucknow cities using Python on the Google Collab platform. It helped me thoroughly with python and Arc GIS to successfully complete my project. I am very thankful to NASA's GIOVANNI site for providing me AOD data.

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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