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Covid-19 lockdown effect on aerosol optical depth in Delhi National Capital Region, India

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Abstract

Coronavirus cases in India have been steadily increasing since March 2020. COronaVIrus Disease 2019 (COVID-19) has been managed by a variety of preventative measures. A prominent measure by the Government of India to prevent the spread of Coronavirus Disease 2019 (COVID-19) began on March 25, 2020, with a complete suspension of all outdoor activities throughout the country. Such complete lockdown has resulted in a decrease in anthropogenic emissions, which is partly due to restrictions on human activities. Delhi National Capital Region (NCR), a landlocked area, suffers from high amounts of aerosols due to both natural and anthropogenic sources. The present research focuses on changes in Aerosol Optical Depth (AOD) prior to and during lockdown (initial and second lockdown phases) around satellite cities (Faridabad, Ghaziabad, Gautam Budh Nagar and Gurugram) of Delhi using high-resolution MODIS AOD product. With the implementation of lockdown measures in phase I and phase III of the current study region, AOD decreased dramatically, while phase II and phase IV lockdown phases had a higher concentration of aerosol. An unexpected increase in AOD occurred during the second lockdown compared with the initial lockdown and before the lockdown. Overall, the average percentage change from 2019 to 2020 during first lockdown is -4.44%, while the average percentage change from 2020 to 2021 is 27.63%.

Keywords: *MAIAC, COVID-19, lockdown, satellite cities, aerosol optical depth*

Rezumat. Efectul lockdown-ului din perioada Covid-19 asupra adâncimii optice a aerosolilor în regiunea capitalei naționale Delhi, India

Numărul cazurilor de Coronavirus din India a fost într-o continuă creștere începând cu luna martie 2020. Pentru a face față epidemiei de Covid-19 au fost luate mai multe măsuri preventive. Una dintre cele mai importante măsuri luate de către guvernul Indiei pentru limitarea răspândirii virusului și a bolii a fost luată începând cu 25 martie 2020, și a presupus suspendarea tuturor activităților în aer liber pe tot teritoriul statului indian. O astfel de situație a dus la o diminuare a emisiilor antropice, parțial datorită restricțiilor impuse activităților umane. Regiunea Capitalei Naționale Delhi, o regiune fără ieșiere la mare, se confruntă cu o cantitate mare e aerosoli, generată atât de factori naturali, cât și antropici. Lucrarea de față analizează schimbările în Adâncimea Optică a Aerosolilor (AOA înainte și în perioada de lock-down (faza de lockdown inițial și următoarea) în cazul orașelor satelit ale capitalei (Faridabad, Ghaziabad, Gautam Budh Nagar și Gurugram), folosind MODIS AOD de mare rezoluție. O dată cu implementarea măsurilor de lockdown din faza I si III, în aria studiată AOA a scăzut considerabil, în timp ce în fazele II și IV s-a înregistrat o concentrație mai mare de aerosoli. O creștere neașteptată a AOA a fost sesizată în cea de a doua perioadă de lockdown, comparativ cu situația din perioara primului lockdown și cea premergătoare acestuia. Per ansamblu, schimbările medii procentuale din 2019 si 2020 pentru prima perioadă de lockdown au fost de -4,4%, în timp ce pentru a doua perioadă, 2020-2021 de 27.63%.

Cuvinte-cheie: *MAIAC, Covid-19, lockdown, orașe satelit, adâncimea optică a aerosolilor*

Introduction

COronaVIrus Disease 2019 (COVID-19) emerged in December of 2019 and spread rapidly around the world (Suvarna Fadnavis et al., 2021). The meteorological conditions and pollutants favoured the quick outbreak of the COVID-19 pandemic (Jiang et al., 2021; Lolli & Vivone, 2020; Simone, Ying-Chieh, Sheng-Hsiang, & Gemine, 2020) which had caused 3,588,773 cases and 247,503 deaths globally as on 6 May, 2020 (Bedi, Dhaka, Vijay, Aulakh, & Gill, 2020). To control the spread of COVID-19, the lockdown restrictions were enacted in January in China and afterward in other nations worldwide (Chauhan & Singh, 2020; Paital, 2020; Yunus, Masago, & Hijioka, 2020). In China, the USA, Spain, variations in meteorological parameters and a decrease in concentrations of air pollutants have been noted

during lockdown (Tobías et al. 2020; Muhammad et al. 2020; Baldasano 2020; Nurshad and Farjana 2020; Sanap 2021). India confirmed its first case of COVID-19 on January 30, 2020, and until May 6, 2020, 49,391 cases and 1,694 deaths were reported (WHO (2020b), 2020). In India, a Janata curfew (Public Curfew) was initiated on 22 March 2020, and then on March 25, 2020, a very tight state-wide lockdown was implemented to stem the spread of the virus, COVID-19 (Chauhan & Singh, 2020; Government of India, 2020). Residents were barred from leaving their houses, and public transportation (railways, roads, and airports), industries, and companies were closed except for essential services. Such COVID-19 pandemic lockdown has an impact on air quality in India.

Prior to lockdown, India had suffered immensely from severe air pollution resulting from recent economic growth, traffic emissions, and land-use changes for decades (World Bank and International report 2020; Fadnavis et al. 2013; Guttikunda et al. 2014; Hama et al. 2020). Such acute pollution resulted in an increase of 2.6 hazy days per year and a death rate of 8.8% (Council & Medical, 2017; IHME, 2019; Thomas, Sarangi, & Kanawade, 2019). India ranked fifth in the world in terms of particulate matter ($PM_{2.5}$). Moreover, India lead the list of the world's smoggiest urban districts, accounting for 21 of the top 30 most polluted cities (WAQR, 2019). Ten of the top 21 polluted cities were in Delhi, National Capital Region (NCR) (World Air Quality Report 2020, 2020). Increasing industrialization, commercialization, and urbanization have all adversely affected the air quality in National Capital Region. Delhi's polycentric growth had led to the proliferation of motorized vehicles and industrial activities in its surrounding areas, viz. Faridabad, Gurugram, Gautam Budh Nagar, and Ghaziabad etc. causing many pollutants (PM, NOx, SOx, NH3, O3) (Garg & Gupta, 2019; Gulia, Nagendra, & Khare, 2017; Kumar, Ghosh, Hooda, & Singh, 2019; Kumar, Ghosh, & Singh, 2022; K. Ranjan, Sharma, & Ghosh, 2022; S. K. Sharma et al., 2014; V. Sharma, Ghosh, Kumari, et al., 2022; V. Sharma, Ghosh, Singh, et al., 2022; S. Singh & Peshin, 2014).

Even with such high levels of pollution, India had also experienced improved air quality during the lockdown since the level of anthropogenic activities have been reduced (Chen, Huang, Yuan, & Tan, 2020; M. Jain, Taubenböck, & Namperumal, 2011; Muhammad et al., 2020; Shukla, Sharma, Baruah, Shukla, & Gargava, 2020; Tobías et al., 2020; Xu et al., 2020). Earlier research have reported the impact of first lockdown phases on air quality measures using wide range of pollutants in India and across the globe (Dantas, Siciliano, França, da Silva, & Arbilla, 2020; Garg & Gupta, 2019; Li et al., 2020; S. Sharma et al., 2020). A significant decline in AOD_{MAIAC} (0.16) throughout the Indian landmass has been reported (Mishra & Rathore, 2021). North India had a 40% decrease in aerosol levels (Suvarna Fadnavis et al., 2021; S. Gautam, 2020; S. Jain & Sharma, 2020, Le Quéré et al., 2020), while over Southern India, the AOD_{MAIAC} levels were increased due to local biomass burning (Le Quéré et al., 2020; Pandey & Vinoj, 2021; Sanap, 2021; T. Singh et al., 2020). As part of the current study area, Gautam Budh Nagar, Gurugram, and Ghaziabad have recorded a 55-65% reduction in PM_{10} and $PM_{2.5}$, and the AQI has improved (Garg & Gupta, 2019).

Effect of first lock down over different parts of India have been examined in various research published earlier (A. S. Gautam et al., 2021; Pathakoti et al., 2021; Pramod, 2021; Rani & Kumar, 2022). However, no study analyzed the spatial-temporal variation of Aerosol Optical Depth (AOD) at a micro-scale during the second lockdown in 2021 for the current study area. Considering the importance of micro-level study for designing the area-specific management plan, present research utilized AOD_{MAIAC}, obtained at high temporal and spatial resolution (daily at 1 km) and compares the percentage of AOD variations from pre-lockdown (2019) to first lockdown (2020) and second lockdown (2021) periods. Further, previously published research highlighted the rise in AOD from pre-lockdown period (from January 2020 to March 2020-winter + pre-monsoon) to first lockdown period (from March 2020 to May 2020-pre-monsoon) to post-lockdown period (from May 2020 to July 2020-pre-monsoon + monsoon). However, such rise in AOD could not be considered as the sole effect of lockdown, as the aerosol concentration could be modified during different seasons because of the influence of climatic parameters (V. Sharma, Ghosh, Bilal, Dey, & Singh, 2021). Therefore, in the present research, to examine the lone effect of lockdown over the variation of AOD, same time frame is used (keeping the season constant) and the variation of AOD has been analysed during lockdown, pre-lockdown, and post-lockdown periods.

Site Description

The present study area, located in the semi-arid climatic zone of India includes parts of Delhi's National Capital Region (NCR), Gautam Buddha Nagar and Ghaziabad of Uttar Pradesh (28.33°N - 77.60°E), Gurugram and Faridabad of Haryana (28.31°N – 77.33°E) (Fig. 1). Since the last decade, these districts of NCR have experienced rapid urbanization and industrialization accompanied by acute air pollution and high temperature (Ghosh, N., Kumar, & Midya, 2021; Kumar, Midya, Ghosh, & Singh, 2021).

In NCR, apart from the natural sources, traffic density, industrial operations, construction works, dust re-suspension, biomass burning, and regional pollution transit are the anthropogenic drivers of particulate matter concentrations ($PM_{2.5}$ and PM_{10}). Ghaziabad was the most polluted city in South Asia, followed by Noida (ranked fifth), Gurugram (ranked sixth), Greater Noida (ranked eighth), and Faridabad (ranked eleventh) (WAQR 2019). This region lacks scientific studies on particle pollution, despite its rapid expansion and high levels of air pollution. Within the current study area, the first lockdown was imposed from 24 March 2020 to 31 May 2020 and the second lockdown was from 5 April, 2021 to 15 June, 2021.

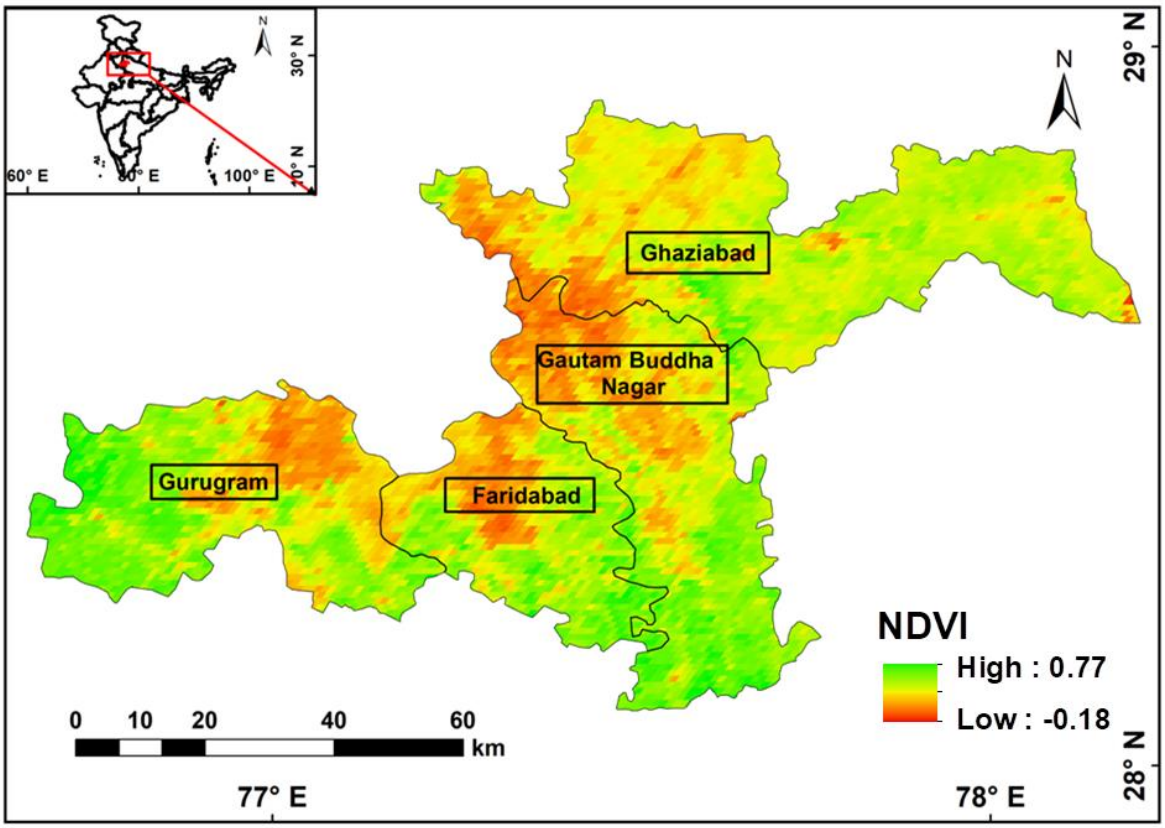

Fig. 1: Study area description shown in MODIS NDVI product (MOD13A2)

Depending on the severity of infection rate and number of COVID cases, all 727 districts across the country were divided into three zones (red, orange, and green). The red zone areas had highest incidence of cases and lockdown was maintained in the red zones. The area where not even a single case reported in last 14 days were categorized as orange zone and only private, hired cars, not public transportation, were permitted in orange zones. Ggreen zone designated the area where no case had been reported in the last 28 days and normal travel was permitted, with buses limited to 50 percent capacity. The Red Zone covered Faridabad, and Gautam Budddha Nagar, the Orange Zone covered Gurugram, and Ghaziabad. Red zones have a high number of coronavirus infections and a high doubling rate, orange zones have fewer cases than red zones, and green zones had no cases in the previous 21 days.

Methods and materials

Instrument/Products/Software

The most recent version of the Multi-angle Implementation of Atmospheric Correction (MAIAC) algorithm have been used to derive aerosol data from MCD19A2 V6 gridded L2 AOD_{MAIAC} at 550 nm. The combined MODIS Terra and Aqua products daily at 1 km resolution have been obtained through https://ladsweb.modaps.eosdis.nasa.gov/. Data from the AOD_{MAIAC} have been processed using MATLAB for the years 2019, 2020, and 2021, and the percent change between the years has been mapped using Origin2022b.

Derivation of AOD from MODIS MAIAC Aerosol Product

MCD19A2 V6 gridded L2 AOD_{MAIAC} at 550 nm, obtained daily at 1 km resolution, has been used as the aerosol data. The combined MODIS Terra and

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Aqua product have been obtained using the most current version of the Multi-angle Implementation of Atmospheric Correction (MAIAC) algorithm (Lyapustin, Wang, Korkin, & Huang, 2018). Such Terra and Aqua MAIAC product (MCD19A2; https://ladsweb.modaps.eosdis.nasa.gov/) have been used to derive AOD_{MAIAC} data at 550nm with Scientific Data Set (SDS) "Aerosol Optical Depth at 550nm" for the year 2019, 2020, and 2021 in the current study. The cloud mask value "clear" for Quality Assurance (QA) indicates that the data is of the highest quality. The AOD_{MAIAC} data has been downloaded through https://ladsweb.modaps.eosdis.nasa.gov/ and processed for 2019, 2020, and 2021 using MATLAB software. During pre-processing, a specific Scientific Data Set (SDS) was extracted, as well as masking of the current study region. AOD_{MAIAC} has been analyzed for air quality assessment in various phases of COVID-19's lockdown (pre-lockdown, during first & second lockdown) (Table 1). The change in aerosol concentrations between PL and FL, SL and FL has been calculated using Equation 1 and Equation 2:

$$\left(\frac{(FL\ concentration - PL\ concentration)}{(PL\ concentration)}\right) * 100 \qquad (1)$$

$$\left(\frac{(SL\ concentration - FL\ concentration)}{(FL\ concentration)}\right) * 100 \qquad (2)$$

The daily AOD_{MAIAC} data has been divided into phases of lockdown for three years, and spatial distribution of AOD has been represented in Figures 2-5. Mean AOD has been calculated by averaging the phased data for a particular year.

Time Frame of the Analysis

To explore the variation of AOD with lockdown explicitly, the analysis period has been divided into three sub-periods and 4 phases of lockdown. Phase 1(P – I) includes: (March 25 to April 14, 2019-Winter to Pre-monsoon) pre-lockdown (PL), (March 25 to April 14, 2020- Pre-monsoon) during first lockdown (FL), (March 25 to April 14, 2021-Pre-monsoon) during the second lockdown). Subsequently, spatial distribution of AOD has been compared from PL to FL to SL during Phase-I, keeping the season constant (Winter to Pre-monsoon). Likewise, AOD has been compared for other phases (Phase 2, Phase 3, Phase 4) (Table 1).

Table 1: Various phases of lockdown [Pre-lockdown (PL), first lockdown (FL) & second lockdown (SL)]

Duration	Details			Activities
P-I	25 March – 14 April	PL	2019	Normal activities
		FL	2020	Non-essential activities (gym, malls, entertainment, cultural etc.) came to halt
		SL	2021	Partial activities allowed (schools, offices remained shut)
P-II	15 April – 3 May	PL	2019	Normal activities
		FL	2020	Previous lockdown has been maintained, and important modifications in policies have been framed as preparation for further lockdown.
		SL	2021	Partial activities allowed (schools, offices remained shut)
P-III	4 May – 17 May	PL	2019	Normal activities
		FL	2020	Region's categorization based on the pandemic and relaxation in restrictions in the red, green, and orange zone
		SL	2021	Partial activities allowed (schools, offices remained shut)
P-IV	18 May – 31 May	PL	2019	Normal activities
		FL	2020	Further relaxation in red zone area where the COVID-19 cases are relatively high
		SL	2021	Partial activities allowed (schools, offices remained shut)

Results and Discussions

The AOD_{MAIAC} has been pre-processed using MATLAB R2019b software for 2019, 2020, and 2021. After the pre-processing, AOD_{MAIAC} has been divided into AOD_{MAIAC} PL, AOD_{MAIAC} FL, and AOD_{MAIAC} SL as discussed in the methodology section. The mean value of AOD_{MAIAC} for these durations has been considered for the study. The highest AOD has been observed during P-III of SL. A drop in AOD has been noted in the P-I of FL. Overall, a change of 5% to 36% has been observed in different phases.

During complete lockdown period in 2020, the aerosol concentration decreased in the current study area compared to PL period in 2019. Similar observations have been reported for Delhi and other parts of northern India by earlier research (Garg, Kumar, & Gupta, 2021; Pathakoti et al., 2021; Pramod, 2021). In 2021, unlike in other parts of India, the present study area was still under partial lockdown. However, contrary to the general expectations, aerosol concentration increased

compared to the FL and PL situations even. Such findings indicate the impact of anthropogenic activities on air pollution which calls for strict policies and its proper implementation to control pollution levels. During this partial lockdown, production in industries gets doubled to meet the increasing demand, which could be one of the probable reasons for abrupt increase in AOD. The other possible reason could be the vehicular emission resulted from cross-border checking which led to rise in AOD concentration. Moreover, drastic increase in AOD over the study area could be attributed to the increased incidents of field-fires for stubble-burning after wheat harvest in Punjab, Haryana and Western Uttar Pradesh (Shahnawaz, 2021). Besides such anthropogenic factor, atmospheric moisture, intricate chemical reactions, surface and upper-air circulation, wind speed could be the driving climatic factors responsible for AOD increase (Pandey & Vinoj, 2021; Pramod, 2021).

Spatial distribution of AOD_{MAIAC} have been depicted phase-wise for 2019, 2020, and 2021during three situations (PL, FL, and SL) in Figures 2-5 to analyse the pattern of AOD anomaly during pre-lockdown and during complete and partial lockdown. The highest AOD recorded were 0.68 (PL), 0.7 (FL) and 0.9 (SL). During P-I, all the four districts in the study area maintain low AOD (0.2-0.5) during FL and SL and even PL. AOD are divided in to four categories a) Low (0-0.2) b) Moderate (0.2-0.5), c) High (0.5-0.8) and d) Very High (0.8-1). During P-I, PL, Ghaziabad and Gurugram were in moderate and low category respectively. During FL AOD decreased compared to the pre-lockdown period. On the contrary, aerosol concentration increased in Gurugram, Faridabad, and Gautam Buddha Nagar.

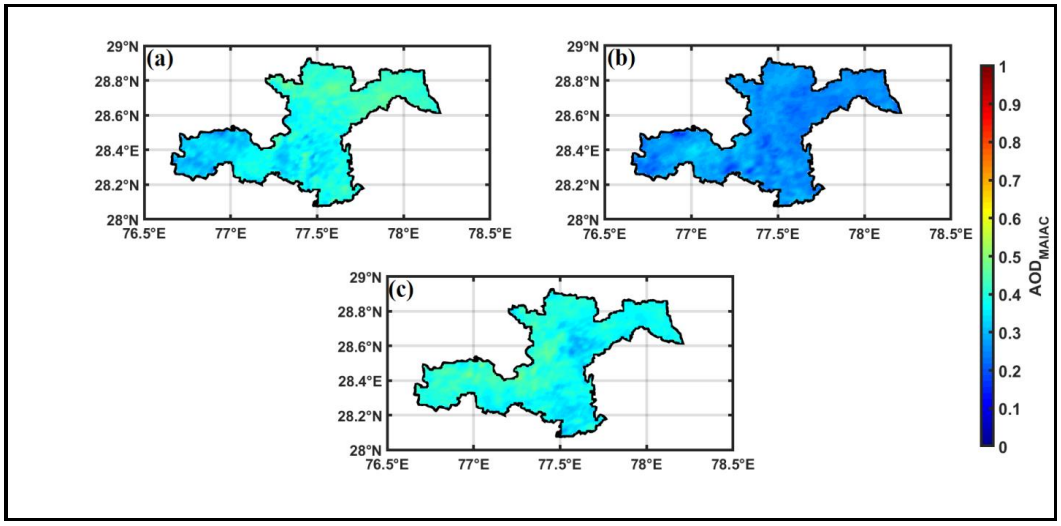

Fig. 2: Spatial distribution of AOD_{MAIAC} during first phase (P-I) a) PL b) FL and c) SL

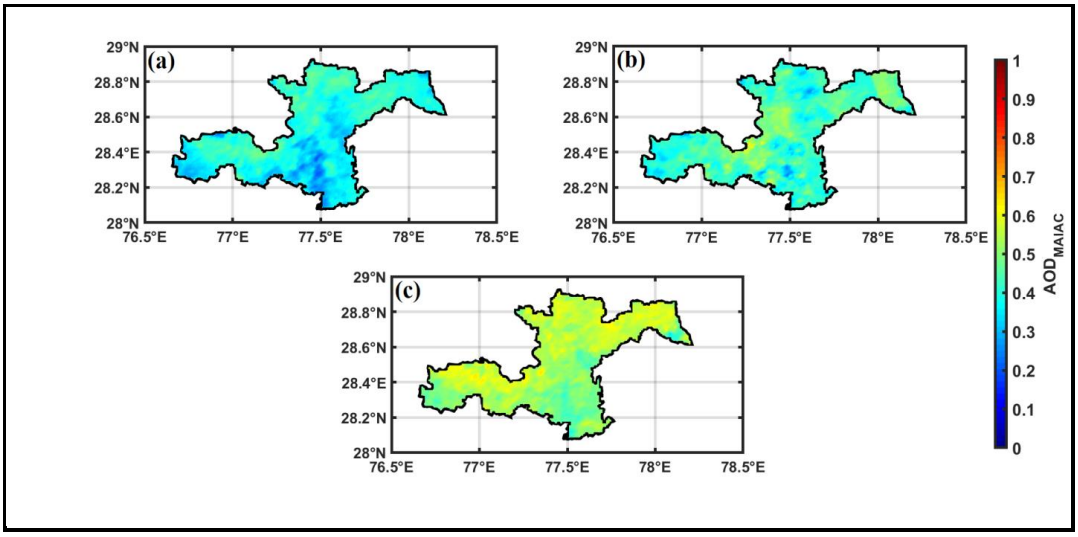

Fig. 3: Spatial distribution of AOD_{MAIAC} during second phase (P-II) a) PL b) FL and c) SL

During P-II, Gurugram and Ghaziabad were in moderate category with respect to AOD, while parts of Faridabad and Gautam Buddha Nagar were in low category in pre-lockdown period unlike P-I. The aerosol concentration has increased during the FL, bringing several portions of Faridabad, Ghaziabad,

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Gurugram, and Gautam Buddha Nagar into the moderate class, which were in low category during P-I. Various anthropogenic activities were typically exempted during P-II lockdown, resulting in an increase in aerosol concentrations during FL. In addition, aerosol concentration during SL has increased over time and the study area now falls into the high category.

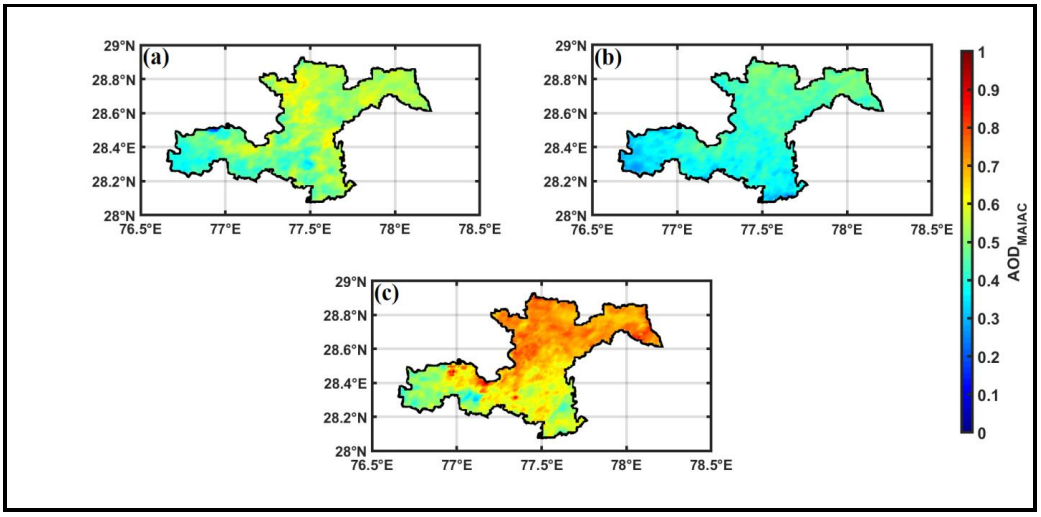

Fig. 4: Spatial distribution of AOD_{MAIAC} during third phase (P-III) a) PL b) FL and c) SL

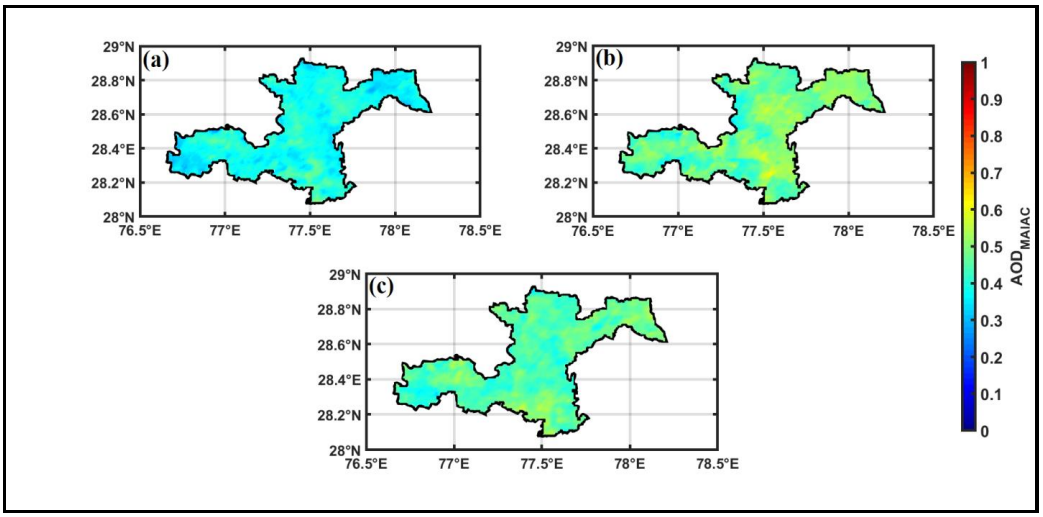

Fig. 5: Spatial distribution of AOD_{MAIAC} during P-IV of a) PL b) FL and c) SL

Compared to P-I and II, an increase in aerosol concentrations have been observed in P-III during pre-lockdown and SL period. However, during FL, aerosol concentration was low due to the reintroduction of restrictions following an increase in COVID-19 cases. High to very high concentration zones have been identified mostly in Gautam Budh Nagar and Ghaziabad.

In P-IV, the aerosol concentration remained moderate during pre-lockdown period, as opposed to P-I and P-II, which had low concentration zones in some areas. Compared to all the preceding phases, the aerosol concentrations during FL increased from moderate to high in P-IV due to relaxation of restrictions as unlocking commenced and then remain moderate during the SL period.

Figure 6 (a) shows the average AODMAIAC for the three periods: Pre- lockdown, during FL, and SL. The percent change in AODMAIAC over time in various phases can be depicted through Figure 6 (b). The lowest and highest AOD has been observed during P-I, FL (0.26) and P-III, SL (0.64) respectively. Prior to the lockdown, prime sources of aerosol in the current study area are emissions from factories, vehicles, and construction projects. The average AOD in pre-lockdown period was 0.3. During the phase one of initial lockdown (P-I, FL), all operations came to a standstill, including emissions from industries, automobiles, and construction resulting into a decrease of aerosol concentration (AOD ~ 0.26). Few necessary activities were allowed to take place during P-II. Therefore, the aerosol concentrations started rising in the Phase-II of FL. In the third phase (P-III),

the entire lockdown was imposed yet again, resulting in a drop in AOD. In the fourth phase (P-IV), the partial lockdown persisted, although there was some relaxation in few areas, contributing to the rise in aerosol concentration and the highest AODMAIAC. Further, during FL, reduction in AOD was observed in the 1st and 3rd phases contrary to 2nd and 4th phases. AOD was higher during SL compared to FL. In 2021, when the second wave of COVID-19 hit the world, the current study area was subjected to a second partial lockdown resulted the fluctuations in AOD.

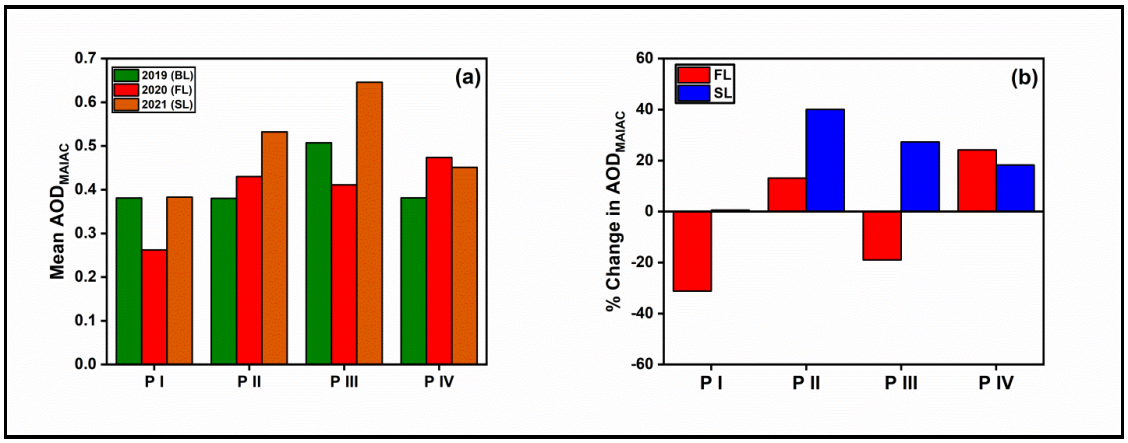

Fig. 6: Representation of (a) Mean AOD$_{MAIAC}$ and (b) percent change of AOD during FL, and SL from pre-lockdown period in PI-IV

Percentage change in in pre-lockdown and during first & second lockdown has been depicted in Figures 6(b), 7, 8. Observed change during SL is positive, indicating that the AOD has been increased during SL compared to FL. The P-II and P-IV has shown a positive percentage change. was attributed to meteorological activities and anthropogenic activities. P-I (-31.19 %) and P-III (-19.01 %), observed a negative change, exhibiting decrease in AOD compared pre-lockdown period due to the complete lockdown and thereby stoppage of the prominent sources of emissions. The anthropogenic and meteorological factors both contributed to the positive shift in P-II (13.11%) and P-IV (24.22%). During the second phase, the most considerable increase was noted in Faridabad and sections of Gautam Buddha Nagar, while the P-IV, substantial increase in AOD occurred throughout the study area (Fig. 7).

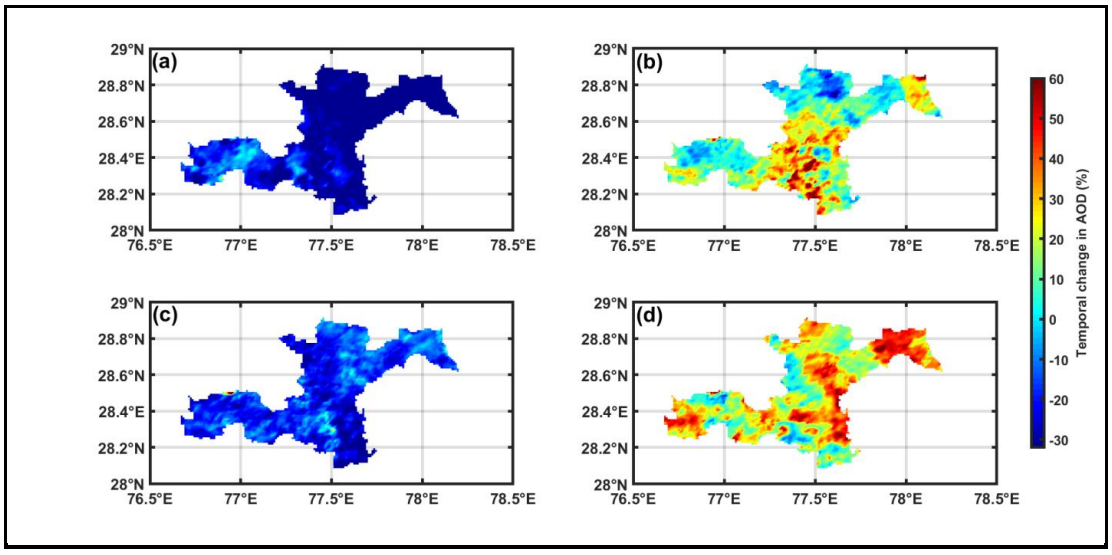

Fig. 7: Phase-wise AOD$_{MAIAC}$ anomaly- FL-PL (2020-2019) (a) P-I (b) P-II (c) P-III and (d) P-IV

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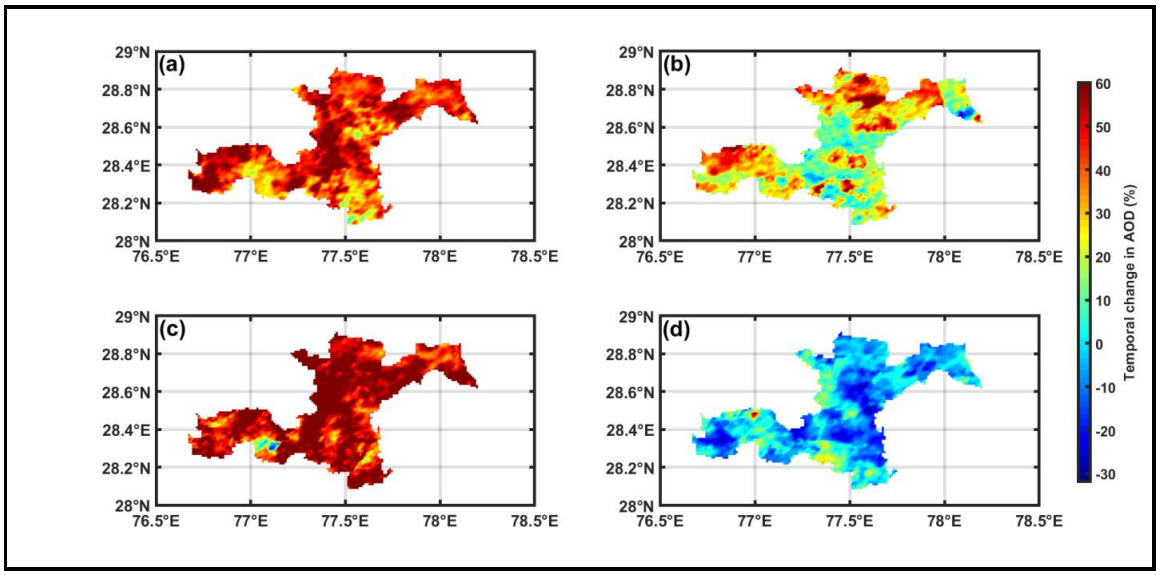

Fig. 8: Phase-wise AOD_{MAIAC} anomaly map of SL-FL (2021-2020) (a) P-I (b) P-II (c) P-III and (d) P-IV

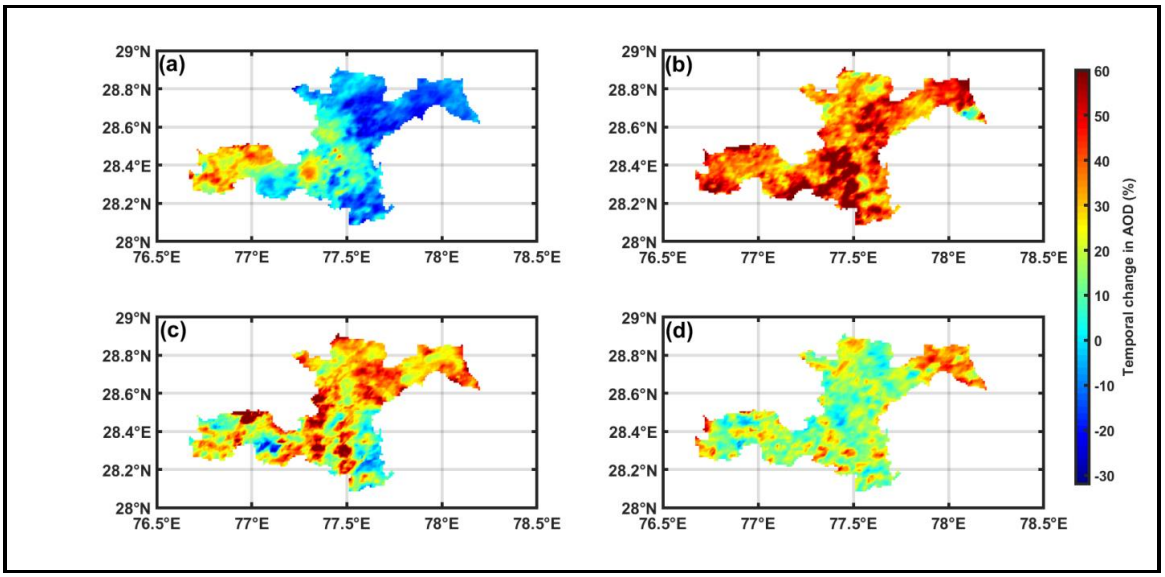

Fig. 9: Phase-wise AOD_{MAIAC} anomaly map of SL-PL (2021-2019) (a) P-I (b) P-II (c) P-III and (d) P-IV

During the SL in first three phases [P-I (46.13 %), II (23.81%), III (57.22 %), and IV (-4.79 %)] the AOD has been increased due to anthropogenic and meteorological activities (Fig. 8). A positive change has been observed during the SL in all the phases [P-I (0.55 %), II (40.03%), III (27.32 %), and IV (18.24 %)] compared to pre-lockdown period (Fig. 9). The highest positive change has been seen in the P-II and the P-III during the second lockdown (Fig. 8).

Various research published earlier reported a reduction in pollution levels in entire north India and the metropolitan cities (Delhi, Kolkata, Mumbai) during the first lockdown compared to pre-lockdown period from 2019 to 2020 and lowest AOD has been measured in April 2020 (Ahamed Ibrahim S.N., Sri Shalini S, Ramachandran A, & Palanivelu K, 2022a; Chinmay et al., 2021; Fatima, Ahlawat, Mishra, Maheshwari, & Soni, 2022; Pramod, 2021; Shahnawaz, 2020; Sudesh, Sushil, Rimpi, & Sudesh, 2021) . Ambient concentration levels in the Gangetic plain remained close to the 24-hour standard limit while in the south, AOD_{MAIAC} levels increased, demonstrating the susceptibility to climate factors (Ahamed Ibrahim S.N., Sri Shalini S, Ramachandran A, & Palanivelu K, 2022b; A. K. Ranjan, Patra, & Gorai, 2020). Present study mainly focused on analyzing the AOD pattern during the first and second lockdown periods (2020-2021) and compared it with pre-lockdown aerosol concentration in 2019. Our study first reported a significant increase in AOD levels

during the second lockdown period compared to the previous times. Contrary to the previous research carried on a regional scale, our micro-level study remarked that COVID-19 pandemic-induced lockdown events significantly improved air quality in India's most polluted cities in some phases, while shocking increase in AOD has been observed in few phases especially during SL due to the leniency of the lock down and transmission of aerosol particles by pre-monsoonal winds. Severely polluted regions throughout the previous decade (Sikarwar & Rani, 2020), had a significant drop in aerosol levels only in the first and third phase of FL. Variations in aerosol concentrations have been detected across all phases due to the intricacies of meteorological and anthropogenic factors.

Conclusion

The COVID-19 pandemic becomes a serious hazard to human health and a significant economic loss over the world. While the pandemic-induced lockdown indicates that nature can heal itself if humans give it a chance, the present research emphasized that pandemic-induced lockdown significantly reduced AOD levels across the top polluted regions. During phase-wise lockdowns in the satellite cities of Delhi, the spatial and temporal variations of AOD have been investigated. From March 25, 2020, to May 14, 2020, the differences in aerosol concentration levels during lockdowns have been examined using AOD_{MAIAC}. AOD_{MAIAC} was lower by around 20% to 90% during lockdown stages. The concentration of aerosol decreased dramatically due to several rigorous measures adopted during the lockdown limiting public and private transportation and halting industrial and commercial activity and thereby significant decreasing local pollutants from vehicle exhaust and industrial activities. Interestingly, during the first phase, the AOD_{MAIAC} levels decreased, however, in the second phase, AOD level increased as the relaxation in restrictions were sanctioned. During the second and fourth phase of FL, the AOD levels were high in comparison to pre-lockdown period. During SL, AOD were higher compared to FL and PL for the current study area in all the four phases which clearly illustrates that proper rule, norms, and standards can keep the ambient air quality in check. Besides the regional scale, our micro-level analysis illustrates the conditions at the local scale and signifies that the chemistry of pollutants in the environment, emission sources, and meteorological conditions together influence the number of pollutants in ambient air. Since the results indicate that vehicles, industry, and construction activities are the primary causes of air pollution in Delhi NCR, severe pollution-reduction measures, as well as regulations and norms tailored to the current circumstances are necessary.

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Author contribution

Conceptualization, S.G; methodology, X.X.; formal analysis, V.S.; investigation, V.S.; S.G. writing—original draft preparation, V.S.; writing—review and editing, S.G.; S; P.K.R.; Resources provision: S.; P.K.R.; S.S. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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