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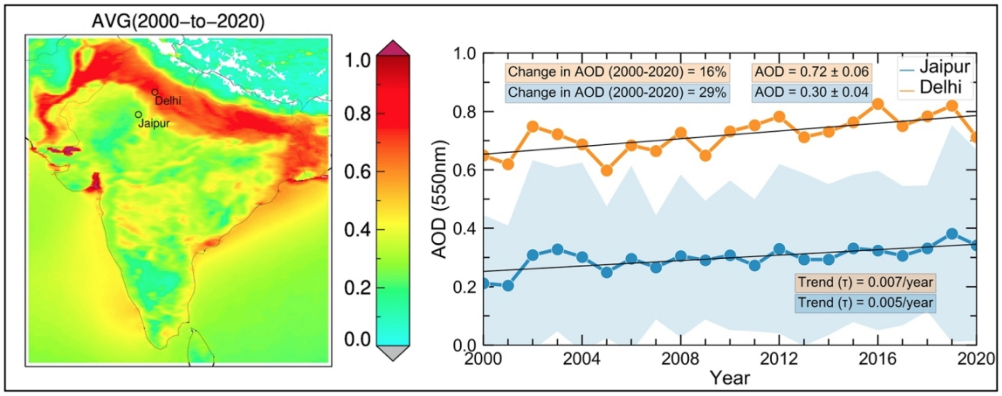
Highlights

- Studied $PM_{2.5}$ and long-term (2000–2020) aerosol optical depth of Jaipur city.
- Observed a 29% increase in aerosol optical depth of Jaipur, but was significantly lower than Delhi.
- Studied the temporal and spatial variability in $PM_{2.5}$ of Jaipur during the 2020 Diwali festival.
- Observed significantly lower $PM_{2.5}$ in Jaipur during 2020 Diwali compared to previous years due to favourable weather conditions and firecracker ban.
- Increase in aerosol optical depth and $PM_{2.5}$ due to crop residue burning was also observed in Jaipur during Diwali week.
- With mobile air quality monitoring, location of a pollution hotspot was also identified.



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Temporal and Spatial Variability in Particulate Matter Pollution in The Pink City during the 2020 Diwali Festival

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Abstract

The temporal and spatial variability of $PM_{2.5}$ in Jaipur during the Diwali festival in the year 2020 is analysed and compared with previous years. Diwali festival is celebrated widely across India every year by bursting firecrackers, which significantly deteriorates the short-term air quality. For the temporal and spatial analysis, we used data from satellite, regulatory ground monitors, and mobile monitoring using a low-cost sensor. The climatological mean Aerosol Optical Depth (AOD) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua and Terra sensor over Jaipur for the period 2000-2020 was 0.3 ± 0.04. The linear trend analysis over Jaipur shows an increase in annual mean AOD at a rate of 0.005/year, with a significant increase in AOD levels (28.9%) in the past two decades. The increase in AOD is mainly due to the increase in dust particles from the Thar desert, enhanced urban activities, and post-monsoon crop-fires. During the Diwali festival in the previous years (2017-19), hourly $PM_{2.5}$ concentrations were exceptionally high during the night-time, whereas due to the firecracker ban and under favourable weather conditions in the year 2020, no major spike in hourly $PM_{2.5}$ concentrations was observed. The daily mean $PM_{2.5}$ concentrations in the previous years (2017-19) were substantially higher Post-Diwali than Pre-Diwali days, whereas the opposite trend was observed during Diwali 2020 due to relatively higher wind speeds. In 2020, AOD levels showed a significant spike on 1-day Post-Diwali, whereas $PM_{2.5}$ concentrations from surface measurements showed a drop. Satellite observations show a layer of smoke over Jaipur transported from crop-fires in Northern India, that lead to a significant rise in both the AOD and $PM_{2.5}$ concentration on the 4th day Pre-Diwali. $PM_{2.5}$ concentrations observed from mobile monitoring were higher Pre-Diwali days than Post-Diwali and did not show much variation during the evening and night-time of Diwali day.

Keywords: Aerosol optical depth (AOD), Spatio-temporal patterns, Mobile $PM_{2.5}$ monitoring, Low-cost sensor, Diwali

1 INTRODUCTION

The promising economic opportunities offered by urbanization, also bring a health penalty due to the rise in air pollution, especially for low-income countries (Wang, 2018). According to WHO, 9 out of 10 people in the world breathe poor air that exceeds the WHO guideline limit of air pollutants (WHO Air Pollution). This bad air quality has drastic effects on the health of both humans and climate, and every year the combination of ambient and household air pollution causes about seven million premature deaths worldwide (WHO Air Pollution), making the population in countries like India extremely vulnerable due to the severity of air pollution in the region.

According to the State of Global Air (2020), the population-weighted annual average $PM_{2.5}$ concentration of India increased by 6.5 μg/m3 between 2010-19, with the annual average $PM_{2.5}$ exposure observed as 83.2 μg/m3 for 2019, which was the highest in the world. It was found that in 2019, air pollution lead to 1.67 million deaths in India, which is 17.8% of the total deaths in the country, leading to an economic loss of $36.8 billion in 2019 alone (Pandey et al., 2020). The State of Global Air (2019) states that air pollution is one of the top three killers in India and it is estimated that more than half of the world's pollution-related deaths occur in India and China collectively. China has taken strict actions to improve the air pollution situation, by reforms such as banning new coal power plants in polluted areas, introducing massive afforestation, and reforestation (Leung, 2021). The introduction of The Air Pollution Action Plan, in 2013 and the Three-year Action Plan for Winning the Blue Sky War, in 2018 have helped China to significantly improve its air quality, whereas India is still in its early days in the fight against air pollution with the introduction of National Clean Air Program in 2019 and an ambitious push towards clean energy with a target to achieve 450 GW renewable energy capacity by 2030, of which 100 GW is installed till now (PIB). But activities like stubble burning and bursting fireworks during the Diwali festival in India hinder India's fight against air pollution. (Chattopadhyay, 2014).

Air pollution has gained attention in recent years from all parts of society in northern India with the pollution levels staying in the severe category in many cities (AQLI, 2021). For the 5,000 cities and towns in India, it was found that around 4000 continuous ambient air quality monitoring stations (CAAQMS) would be required to efficiently monitor air quality variations spatially and temporally but as of September 2019, just 200 CAAQMS are operational in India (India – Ambient Air Monitoring Data).

Due to rapid urbanization and population growth, Jaipur city (also known as the Pink City) ranked as the 14th most polluted city in the world in 2016 (WHO Global Urban Ambient Air Pollution Database, 2016) and was found to be the 22nd most environmentally vulnerable city of the world in 2021 (Environmental Risk Outlook, 2021).

Several past studies reported air pollution issues in the city but gaps in various aspects of spatiotemporal variability remain. The majority of the previous studies used ground-based point measurements to address air pollution issues and focused on a certain time period only. There is still a lack of understanding on spatial and temporal scales of pollutions in the city, specifically during the major festival such as Diwali. We attempt to address and fill in gaps on spatiotemporal variability of PM (or aerosols) in Jaipur during Diwali while using 2 decades of satellite observations of aerosols, multiple regulatory grade air quality monitors, and mobile monitoring using a low-cost sensor. Section 2 provides details on the study area, data and method applied; section 3 presents results on satellite-derived long-term trends, pollution during Diwali and role of meteorology, and spatiotemporal analysis of mobile monitoring; section 4 discusses the results and summary of major findings are reported in section 5.

2 METHODS

2.1 Study Area

In this study, air quality data was analysed for Jaipur, the capital city of the northwestern state of Rajasthan in India. Jaipur has a population of 3.1 million and is the 10th most populous city of India according to the census of 2011 (Census India, 2011).

Jaipur (26.91 °N, 75.78 °E) lies in the foothills of the Aravalli mountain range, surrounded by hillocks on its northern and eastern sides. It has a vast stretch of plains and desert on its western and southern sides. Being located downwind of the Thar desert, dust storms are quite frequent in the region. Jaipur is located about 268 km southwest of the national capital Delhi and witnesses extreme temperatures both in summer as well as in winters and low to moderate RH.

We analyzed the air quality data of Jaipur during the Diwali festival, also known as the festival of lights. The Diwali festival typically falls in the month of October or November (observed according to the moon calendar) every year (Table S1). During the week-long celebration of Diwali, among other practices, the use of firecrackers is common across the country. The use of firecrackers usually results in poor air quality for a short period of time and is well documented and reported in previous studies in different parts of the country (Attri et al., 2001; Kulshrestha et al., 2004; Ganguly, 2009; Deka and Hoque, 2014; Saha et al.,2014; Ganguly, 2015). This is also the time of year when large-scale crop residual burning occurs in several adjunct states (Mittal et al., 2009) and transported smoke can significantly increase the pollution concentration in downwind areas.

According to the study by Pozzer et al. (2020) on the coronavirus pandemic (COVID-19) that emerged in 2019, air pollution was found to be an important cofactor in increasing the risk of mortality from COVID-19 and estimated to have resulted in 15% of worldwide deaths from

COVID-19. $PM_{2.5}$ data from ground stations were used for the year 2014 and found that $PM_{2.5}$ concentrations of Jaipur city were significantly higher during the Diwali day (186 µg/m^3) compared to normal days before (71µg/m^3) and after Diwali (40 µg/m^3) and the air pollution condition in Jaipur were found to be poor ($201<AQI<300$) or very poor ($301<AQI<400$) for a small fraction of days during Diwali (Ganguly et al., 2019), with the AQI mentioned here corresponding to the maximum value of the individual sub-indices of eight pollutants (PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, and Pb). So, in order to prevent the rise in mortality rates from Covid-19 due to the potential spike in air pollution during the Diwali festival in the year 2020, the Government of Rajasthan imposed a statewide ban on the sale and bursting firecrackers to control the air pollution and subsequently Covid-19 mortalities (The Times of India, Twitter).

2.2 Surface Measurements

$PM_{2.5}$ is routinely measured from a reference-grade monitor located at three locations (Police Commissionerate, Shastri Nagar, Adarsh Nagar) in the city (Fig. S9) and operated by Rajasthan State Pollution Control Board (RSPCB). The measurement frequency of the monitoring station is 15 minutes. Reference grade monitor (i.e. BAM) data for the period of 2017-2020 is downloaded from the Central Pollution Control Board (CPCB) database (CPCB, 2020) for this study. In the past studies, data obtained from CPCB monitoring stations were found to have measurement errors of around less than 5% (Sarkawt et al., 2020; CPCB, 2011). To quality control the data, we only used hourly and daily mean concentrations from the CPCB database and eliminated $PM_{2.5}$ concentrations less than 2µg/m^3. Reference grade monitors are also equipped with weather monitors and provide data on wind, temperature, rain, and RH at the same temporal frequency.

2.3 Satellite Measurements

The MODIS sensor onboard NASA's Terra and Aqua satellite has been providing AOD data since 2000 and 2003, respectively. The Terra and Aqua satellites have overpass times of 10:30 am and 1:30 pm local solar time respectively. The MODIS collection 6.1, Level 2 AOD at 550nm with a spatial resolution of 10x10 km^2 of highest quality were used in the study. For analysing the annual AOD trends in Jaipur, the daily AOD data derived from the two MODIS sensors and processed and gridded following the level 3 method explained in our earlier work (i.e. Gupta et al., 2020). For analysing the day-to-day evolution of AOD during the Diwali festival, AOD data for ±14 days of Diwali for the study period (2005-2020) were retrieved from the high-resolution level 3 dataset (Gupta et al., 2020). Similar to the MODIS sensor, the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor onboard NASA's Suomi-NPP satellite has been providing AOD data since 2011. For analysing the aerosol transport to Jaipur city, the Corrected Reflectance (True Color) and Deep Blue AOD maps derived from the VIIRS sensor are downloaded from 10^{th} November and 27^{th} November 2020 for a 2 day period during Diwali using https://worldview.earthdata.nasa.gov/.

2.4 Mobile Measurements

The mobile air quality monitoring experiment in the city was performed by integrating low-cost Purple Air Sensor (PAS) and U-Blox Global Positioning System (GPS) module on the roof of a car (Fig. S1). The measurement height was 1.9 meters above the ground. The system design (Fig. S1) for the low-cost mobile air quality monitoring network was as follows: a) the measurement frequencies of the PAS and GPS module was 1 second (Yadav, 2020); b) the data from PAS and GPS got stored in a CSV file on the RaspberryPi (RP); c) the GPS and RP were powered by a 3s (12.6v) LiPo battery and the PAS was powered by a 5v power bank.

The PAS uses a PMS5003 Plantower sensor. It uses a factory calibration-based algorithm to calculate the PM_1, $PM_{2.5}$, and PM_{10} mass concentration in $\mu g/m^3$ (PurpleAir). The PAS currently outputs 2-minute average data, which makes the sensor not ideal for mobile sensing applications. We modify the sensor outputs frequency and accessed the real-time instantaneous data from PAS over wifi by running the script (Yadav, 2020) on RP. This new setup allowed us to gather air quality measurements as well as geolocation at higher temporal resolution.

We collected the data from the mobile monitoring experiment for a period of 2 days Pre-Diwali (11^{th} November and 13^{th} November), 2 days Post-Diwali (15^{th} November & 16^{th} November), and during Diwali day (14^{th} November: evening and night) to analyze the spatiotemporal $PM_{2.5}$ variations in the city. The PAS data were only collected during the 2020 Diwali festival and to capture spatial patterns in air pollution in different parts of the city, data were collected on multiple routes (Fig. 5). In addition, to verify the output of PAS, several measurements were taken next to a reference-grade monitor (Shastri Nagar Station) and results are presented in Fig. S8.

2.5 Method

Air quality indicators (AOD and $PM_{2.5}$) and meteorological parameters (Wind, Temperature, RH) were used to understand the spatial and temporal patterns. In absence of long-term ground $PM_{2.5}$ data, we used satellite AODs from MODIS for the past 20 years to analyse annual trends whereas $PM_{2.5}$ data was used to see short-term (2017-2020) trends.

To quantify the temporal patterns of air pollution during the Diwali festival in Jaipur, we performed the following analysis: a) hour-to-hour evolution of $PM_{2.5}$ concentration for ± 3 days of Diwali from 2017-2020; b) day-to-day change in $PM_{2.5}$ concentration for ± 14 days of Diwali from 2017-2020; c) day-to-day evolution of AOD for ± 14 days of Diwali from 2005-2020. For analysing the temporal patterns in $PM_{2.5}$ concentrations during the 2020 Diwali festival, we used 2017-2019 mean as the baseline condition, as this was the only data available for previous years from the

CPCB database. While for the temporal patterns in AOD, we used 2005-2019 mean as the baseline. We also used meteorological parameters to understand their role in temporal patterns of $PM_{2.5}$ and AODs. The transport patterns of pollution were qualitatively evaluated using VIIRS true-color images and AOD maps. To quantify the spatiotemporal variations of air pollution during the Diwali festival, we performed mobile monitoring with a low-cost sensor using the time frame of Pre, Post, and during Diwali day on 3 different paths in the city.

3 RESULTS

3.1 Trend in AOD and $PM_{2.5}$

AOD is a measure of the amount of light extinction (by scattering or absorption) by aerosols in the atmospheric column. AOD is measured at specific wavelengths, with 550nm being the common reference wavelength used by satellite AOD products. In the past, many studies (Christopher and Gupta, 2020; Gupta et al., 2006; Liu et al., 2009; Sathe et al., 2019; Donkelaar et al., 2019; Yang et al., 2019) have shown the relationship between AOD and surface $PM_{2.5}$ and found that it is not always linear. The estimation of $PM_{2.5}$ from AOD required complex statistical modeling with additional ancillary data sets. Thus, we have not derived $PM_{2.5}$ from AOD in this study, rather have used AOD as an independent parameter to monitor air pollution variation. The 20-Year mean AOD distribution over India (Fig. 1(a)) for the period 2000-2020 shows highly elevated AOD levels in the Indo-Gangetic Plain (IGP). The IGP is a densely populated region and is home to several industries and power plants, which contribute to pollutions. This severe air pollution scenario and its cause in the region has been well documented in the past (Kumar et al., 2018; Devi et al., 2020; Ojha et al., 2020). The marked circles on the map in Fig. 1(a) show the location of Jaipur and Delhi. Compared to Delhi (AOD=0.72), the 20-Year mean AOD levels observed over Jaipur (AOD=0.3) are lower by a factor of more than 2. Using level 2 and level 3 monthly aerosol products obtained from MODIS, MIRS and Aerosol Robotic Network (AERONET) sensor, (Mangla et al., 2020) showed that for the period of 2010-2017, AOD values in Jaipur were lower than other regions in IGP.

Fig. 1(b) shows the time-series of annual mean AODs for the past two decades. The marker represents the annual mean AOD and the shaded area represents one standard deviation (SD). The AOD over both Jaipur and Delhi showed a consistent and increasing trend, with trends being 0.005 and 0.007 per year for the two cities respectively. The AOD values increased to (0.34 ± 0.33) from (0.21± 0.23) for Jaipur over a period of 20 years, which is equivalent to about a 29% increase. Jaipur being an arid region and its proximity to Thar desert, Ramachandran et al. (2012) showed that the increase in wind speed observed over Jaipur from 2000-2009 lead to an increase in soil-derived dust particles, which subsequently resulted in an increasing annual AOD trend (43.2%) over Jaipur. While the increasing trend in AOD over Delhi was attributed to an increase in the amount of aerosols from fossil fuel and biomass burning (Ramachandran et al., 2012). By converting satellite-derived AOD to surface $PM_{2.5}$, Dey et al. (2020) found that between 2000-19, the Thar desert showed a decreasing trend in $PM_{2.5}$ while Jaipur and Delhi showed an increasing trend due to the post-monsoon burning activities (Chowdhury et al., 2019). Whereas Mangla et al. (2020) reported high AOD over Jaipur during the months of April to June for the period 2010-2017 due to dust activities from the Thar Desert, Arabian Peninsula, and Gulf regions (Verma et al., 2013).

Fig. 1(c) shows the annual box-plot of $PM_{2.5}$ concentrations over Jaipur and Delhi for the period 2017-2020. In Fig. 1(c), the box represents 25th and 75th percentiles, whisker represents the minimum and the maximum, horizontal line represents median and the circle represents mean. The annual mean $PM_{2.5}$ observed in Jaipur was 78 ± 53.2, 75.6 ± 32.9, 60.9 ± 27.7, and 53.4 ± 24.4

μg/m^3 between the period 2017-2020 respectively. Compared to Delhi (102.6 ± 93.5), the 4-Year mean $PM_{2.5}$ observed over Jaipur (67 ± 34.6) is lower by a factor of 1.5.

Although the annual mean $PM_{2.5}$ over Jaipur has been relatively lower than in Delhi, it is still remarkably higher than the annual mean WHO air quality guideline (10 μg/m^3).

3.2 Air Pollution during Diwali as viewed from Surface and Satellite

The use of firecrackers is common to celebrate Diwali in India and it often generates harmful pollutants. Here, we analysed the hourly evolution of $PM_{2.5}$ from surface measurements in Fig. 2(a) for ± 3 days of Diwali in 2020 and the previous years (2017-19), to assess the impact of firecrackers and meteorology on air pollution in the city.

Fig. 2(b) shows the box plot of day-to-day evolution in $PM_{2.5}$ from surface measurements for ± 14 days of Diwali in 2020 and the previous years (2017-19), while Fig. 2(c) gives the long-term perspective of air pollution during Diwali using the mean AOD data from the two MODIS sensors, showing the day-to-day evolution in AOD for ± 14 days of Diwali in 2020 and the previous years (2005-19).

3.2.1 Diurnal and Day-to-Day Variability

Typically during Diwali, the peak firecracker bursting activities start late in the evening and last till around midnight and it extends about ±3 days around Diwali day. Hourly $PM_{2.5}$ for the previous years (2017-19) show an increase in value starting around 7 pm, peaks around midnight, and remains high until the next morning. The peak hourly $PM_{2.5}$ during Diwali night was reported as 834, 622, 881, and 149 μg/m^3 for 2017, 2018, 2019, and 2020 respectively. This pattern of rise in $PM_{2.5}$ concentrations at night-time can be observed on Diwali day and for 2 days following Diwali in the previous years (2017-19). But in 2020 (red line on in Fig. 2(a)), no rise in hourly $PM_{2.5}$ values was observed.

This periodic rise in $PM_{2.5}$ concentrations during Diwali week in the previous years (2017-19) is associated with firecrackers, but the firecracker ban in 2020 seemed to have stopped this pattern during the Diwali festival.

The surface $PM_{2.5}$ analysis is extended in Fig. 2(b) using daily mean values for ± 15 days of Diwali to understand the impact on daily mean values from the use of firecrackers. Similar to hourly data, daily mean data consistently shows lower values in 2020 compared to previous years. Fig. 2(b) shows that overall $PM_{2.5}$ values in the pre-Diwali period were consistently lower in 2020 compared to other years, whereas they were higher in the post-Diwali period.

The daily mean (table 1) for Diwali for 2017-2019 varies between 114 ± 136 and 245 ± 231 whereas remains low in 2020 (106 ± 37). Table 1 shows the daily mean $PM_{2.5}$ ± SD value for ± 3 days of Diwali in 2020 and the previous years (2017-19). From Table 1, we can observe the drop in daily mean $PM_{2.5}$ concentrations for days following Diwali in 2020, with daily mean $PM_{2.5}$ being 106 ± 37 on Diwali day and 79 ± 15, 63 ± 15, 56 ± 18 μg/m^3 for the 3-day period following Diwali respectively. The daily mean $PM_{2.5}$ showed a decreasing trend in 2020 after Diwali, whereas it showed an increasing trend in previous years (2017-19).

3.2.2 Impact of meteorology

Meteorological factors such as wind speed, temperature, and RH have a significant influence on air pollution patterns (Cichowicz et al., 2020; Liu et al., 2020; Chen et al., 2020; Jayamurugan et al., 2013; Dey et al., 2017). Fig. S2 shows the hourly wind speed data for ±3 days of Diwali in 2020 and the previous years (2017-19). Typically winds are calm during early winter in the City. Hourly wind speed observed at midnight (12 am) on Diwali day were 0.61, 1.02, 0.05, and 1 m/s for the period 2017-2020 respectively. Despite the similarity in wind speeds at 12 am on Diwali night in 2018 and 2020, the $PM_{2.5}$ concentrations between 2018 and 2020 differed significantly and were observed as 622 and 149 μg/m^3 respectively. This clearly shows a factor other than just higher wind contributing to lower $PM_{2.5}$ concentrations in 2020.

From Fig. S2, we can also observe a periodic rise in the hourly wind speed for the years 2018-2020 during the Diwali week that starts at around 7 am in the morning and lasts till around 7 pm in the evening, with wind speeds peaking at around 12 pm. Due to the elevated wind speeds during the afternoon time (Fig. S2), from Fig. 2a we can observe a periodic dip in the hourly $PM_{2.5}$ concentrations that starts at 7 am in the morning and lasts till around 7 pm in the evening, with the lowest concentrations observed at around 13 pm. This increasing trend in the hourly wind speed between 7 am to 7 pm, leads to a decreasing trend in the hourly $PM_{2.5}$ concentrations between 7 am to 7 pm during the ± 3 days of the Diwali week.

Fig. S3 shows the daily box plot of wind speed for ± 3 days of Diwali in 2020 and the previous years (2017-19). Compared to previous years (2017-19), the daily mean wind speed shows a significant rise Post-Diwali in 2020, thus leading to the drop in daily mean $PM_{2.5}$ concentrations in 2020, as observed in Fig. 2b and Table 1. Fig. S6 also shows an increasing trend in the daily mean values of both wind speed and RH Post-Diwali day in 2020, thus leading to a drop in $PM_{2.5}$ levels Post-Diwali.

Fig. S4 and Fig. S5 show the scatter plot of wind speed and RH with $PM_{2.5}$ respectively using the dataset of ±3 days of Diwali for 2020 and the previous years (2017-19). Fig. S4 shows the expected inverse relationship between wind speed and $PM_{2.5}$ in the previous years (2017-19), with values going beyond 600 μg/m^3 at low wind speeds. Whereas in 2020, the $PM_{2.5}$ concentrations were always below 200 μg/m^3 even at low wind speeds. From Fig. S5, we can observe that RH was significantly higher in 2020 than in previous years, thus this could one of the reasons for lower $PM_{2.5}$ concentrations observed in 2020.

3.3 Spatial distribution of air pollution during Diwali 2020

3.3.1 Citywide monitoring stations

Often air quality variability within a city depends on many factors, such as meteorology (Cichowicz et al., 2020; Liu et al., 2020; Chen et al., 2020; Jayamurugan et al., 2013; Dey et al., 2017), vehicular emissions (Sindhwani and Goyal, 2014; Guttikunda et al., 2014) and traffic density and patterns (Thaker and Gokhale, 2016), and short and long-range transport. To analyse the spatial variation of air pollution in Jaipur city during Diwali 2020, we evaluated the $PM_{2.5}$ and wind speed data of Jaipur's 3 monitoring stations.

Fig. 3(a) shows the daily mean $PM_{2.5}$ concentrations for ±14 days of Diwali 2020 for the 3 monitoring stations of Jaipur. The 3 monitoring stations showed a high correlation in daily mean $PM_{2.5}$ concentrations, thus showing the less spatial variability exhibited by $PM_{2.5}$ in Jaipur during Diwali week in 2020. Due to the increasing trend in wind speeds (Fig. 3(b)) from 1-day Pre-Diwali to 1-day Post-Diwali, there was a decreasing trend in $PM_{2.5}$ (Fig. 3(a)) between 1-day Pre-Diwali to 2nd day Post-Diwali. The wind speed observed at the Adarsh Nagar monitoring station in Fig. 3(b) was found to be significantly higher than the other two stations. But these higher wind speeds observed at Adarsh Nagar station didn't seem to have any visible impact on $PM_{2.5}$ concentrations, as all the stations seem to have similar concentrations, despite a significant difference in wind speeds.

Fig. S7 shows the hourly $PM_{2.5}$ and wind speed data of the city's 3 monitoring stations for the 5 day period (1-day Pre-Diwali to 3rd day Post-Diwali) during Diwali. From Fig. S7, it can be seen that at 12 am on Diwali night, Adarsh Nagar and Shastri Nagar monitoring stations had higher wind speed (1.71 m/s and 1.85 m/s respectively) than the Police Commissionerate monitoring station (1 m/s), and due to the higher wind speeds, lower $PM_{2.5}$ concentrations (93 μg/m^3 and 90 μg/m^3 respectively) than Police Commissionerate station (149 μg/m^3).

3.3.2 Impact of aerosol transport

To track and monitor the long-range transport of aerosols around the world, satellite data has acted as a very reliable source. Some common types of aerosol transport are from biomass burning (Gupta et al., 2007; Huff et al., 2017; Cusworth et al., 2018; Wang and Christopher, 2006), dust storms (Yu et al., 2019; Naeger et al., 2016), and volcanic eruption (Flower and Kahn, 2020), which occur at various spatiotemporal scales. Fig. 4(a) shows an example of aerosol transport from crop-fires in Northern India to Jaipur on the 4th day Pre-Diwali in 2020, where the Corrected Reflectance (True Color) and Deep Blue Aerosol Optical Thickness data taken by the VIIRS sensor (Fig. 4(a)) shows very high AOD values and thick smoke over Jaipur. Similarly, the surface measured $PM_{2.5}$ (Fig. 3(a)) and MODIS derived AOD (Fig. 2(c)) also showed a significant spike in values on the 4th day Pre-Diwali. Whereas the VIIRS sensor data on the 13th day Post-Diwali (Fig. 4(b)) shows very low AOD distribution and a clear sky over Jaipur, similarly the lowest surface measured $PM_{2.5}$ (Fig. 3(a)) was also observed on the 13th day Post-Diwali during the Diwali week.

3.4 Air pollution observed by mobile monitoring during Diwali 2020

Reference grade monitors have high temporal coverage, but due to their static nature, they fail to provide information about the spatiotemporal air pollution variation in a region. Mobile monitoring with low-cost air quality sensors gives us the ability to have a wide spatial coverage with the same sensor unit and generate spatiotemporal data at fraction of cost. In the past, there have been few studies focused on mobile air quality monitoring in India by integrating low-cost air quality sensors on a car. Agarwal et al., 2020 used an optical $PM_{2.5}$ sensor and retrofitted around 20 OLA cabs with them to perform mobile air quality monitoring in Delhi. CSTEP and ILK Labs, 2020 used DustTrak II aerosol monitor to measure $PM_{2.5}$, MicroAeth to measure Black Carbon and condensation particle counter to measure Ultrafine particles, and performed monitoring for 110 days using a CNG car in Bengaluru.

Fig. 5 shows the 3 different paths (Path A, B, C) we chose for mobile monitoring in Jaipur and the spatial $PM_{2.5}$ concentrations observed on different paths during different days of the experiment. We performed the mobile monitoring experiment on Path A on 11th November between 8:39 am to 9:06 am and observed very high mean $PM_{2.5}$ concentration (238.8 μg/m^3) and spatial variability (SD = 53.6).

We performed the mobile monitoring experiment on Path B 5 times between 13th - 15th November. On 13th November, we performed the experiment during morning and night time. During the morning experiment on Path B1 between 9:15 am to 10:10 am, we observed both high mean $PM_{2.5}$ concentration (115.3 μg/m^3) and spatial variability (SD = 31.2). During the night experiment on Path B2 between 9:02 pm to 9:50 pm, the mean $PM_{2.5}$ concentration increased to (196.5 μg/m^3) and showed high spatial variability (SD = 34.2). This increase could be due to the dense traffic at night time, as lots of people go for shopping activities a day prior to Diwali. On 14th November (Diwali day), we performed the experiment on Path B3 between 4:07 pm to 4:41 pm and observed a drop in both mean $PM_{2.5}$ concentrations (93.4 μg/m^3) and spatial variability (SD = 15.6). Similar results were observed during the experiment on Diwali night, on 15th November between 12:02 am to 12:37 am. The mean $PM_{2.5}$ concentration observed on Path B4 during the mobile monitoring experiment on Diwali night was (92.3 μg/m^3), with very little spatial variability (SD = 9.6). Due to high wind speeds and the firecracker ban imposed during Diwali 2020, no spike in $PM_{2.5}$ concentration was observed from mobile monitoring on Diwali night. On 15th November, the morning following Diwali, we performed the experiment on Path B5 between 11:30 am to 12:30 pm, and observed a rise in both mean $PM_{2.5}$ concentration (123 μg/m^3) and spatial variability (SD = 19.7).

On 16th November, we performed the mobile monitoring experiment on Path-C between 6:45 am to 9:40 am. Due to heavy rains and high wind speeds (SF-3, SF-6) on 15th November, we observed a drop in the mean $PM_{2.5}$ concentration (92.2 μg/m^3) on 16th November with high spatial variability (SD = 31.5).

Table 2 shows the path travelled, mean $PM_{2.5}$ ± SD value, distance covered (km), and duration of monitoring (minutes) for each mobile monitoring experiment. From Table 2, we can observe that $PM_{2.5}$ levels were significantly higher Pre-Diwali than during and Post-Diwali. During Diwali day, the $PM_{2.5}$ levels were almost consistent, with mean $PM_{2.5}$ being 93.4 ± 15.6 and 92.3 ± 9.6 μg/m^3 in the evening and night experiment respectively. Similar to the observations from the reference-grade monitor during Diwali 2020 (Fig. 2(a)), we did not observe any spike in $PM_{2.5}$ concentrations from mobile monitoring on Diwali night. The total distance travelled on different paths in Jaipur city during mobile monitoring was 108.04 km and the total duration of sensing was 265 minutes.

Fig. 6 shows the time-series plot of $PM_{2.5}$ concentrations observed during mobile monitoring. The purple air sensor has a temporal resolution of 1 second. From Fig. 6, we can observe the $PM_{2.5}$ variation on each path with time. On Path A, we observed high spatiotemporal variability, as $PM_{2.5}$ concentrations changed significantly with time. Similarly, high spatiotemporal variability could be observed on Paths B1, B2, and C. Whereas on Paths B3, B4, and B5, $PM_{2.5}$ showed less variability with time.

From the mobile monitoring plots on different paths (Fig. 5), we located a pollution hotspot. Fig. S9 shows the location of the pollution hotspot, where we observed a spike in $PM_{2.5}$ concentrations during the mobile monitoring experiment. Due to the ongoing flyover construction, this region is packed with traffic jams and the construction activity leads to an increase in the concentration of dust particles. The data we generated from our experiment shows how impactful mobile monitoring could be to generate fine-grained $PM_{2.5}$ data for regions like Tier-2 cities and rural areas, that currently lack sufficient monitoring capabilities. In 2017, a study found that there should be around 26 reference-grade monitors in Jaipur to efficiently monitor pollution levels in the city (Urban Emissions, 2017), but the number currently stands at only 3. Thus, the accurate results we achieved from our experiment clearly show that low-cost mobile air quality monitoring can bridge the gap in the lack of monitoring capabilities for Indian cities at a fraction of cost.

4 DISCUSSIONS

The rising impact of urbanisation, post-monsoon stubble burning from northern states of India, and dust particles from the Thar desert have contributed to the rise in AOD over Jaipur from 2000-2020. While the $PM_{2.5}$ concentrations were found to be substantially higher than the annual mean safe limit of 10μg/m^3 for the past 4 years, showing the impact of air pollution on even the Tier-2 cities of India.

From the temporal analysis of $PM_{2.5}$ during the Diwali festival, firecracker activities were found to be the primary cause of the pattern of a sudden rise in hourly $PM_{2.5}$ concentrations, which peaked at the night-time during Diwali days in the previous years (2017-19). The ban imposed by the State Government on bursting firecrackers due to Covid-19 during Diwali in 2020, prevented this pattern of sudden elevation in hourly $PM_{2.5}$ concentrations from occurring during the night-time of Diwali, showing the impact of firecrackers on air quality. A significant impact of wind speed and RH was also observed on $PM_{2.5}$ concentrations during Diwali. The increasing trend in wind speed and RH from Pre to Post Diwali days in 2020, led to a drop in daily mean $PM_{2.5}$ concentrations from Pre to Post Diwali days, whereas the opposite trend in $PM_{2.5}$ concentrations was observed in the previous years (2017-19).

From the spatiotemporal analysis of $PM_{2.5}$ during the Diwali festival on different days and paths, mobile monitoring was found to be a cheap substitute for static reference-grade monitors. Mobile monitoring using low-cost sensor showed patterns similar to reference-grade monitors, showing its potential as a cheap alternate for performing air quality in Tier-2 cities of India.

5 SUMMARY AND CONLUSIONS

Diwali festival creates a unique environmental condition where emissions of air pollutants from different sources like firecrackers, increased human (and industrial) activities and crop-fires get combined and drastically deteriorates the air quality of IGP and neighbouring regions. Calm winds and low temperatures coincident with the festival season favour the poor air quality conditions. To curb the COVID-19 pandemic in Jaipur, the government had imposed a ban on bursting firecrackers during Diwali 2020. In this study, to evaluate the spatiotemporal variability in particulate matter (or aerosols) during the Diwali festival, we performed a comprehensive analysis using data from the MODIS and VIIRS sensor, three regulatory ground monitors, and mobile monitoring using a low-cost sensor. The end goal of the analysis is to assess the impact of the firecracker ban and meteorological aspects on air pollution during Diwali. In addition, we have also analysed long-term trends in particle pollution over the city.

The key findings from our analysis are:

- The climatological AOD derived from the two MODIS (Aqua and Terra) sensors over Jaipur and Delhi in the period 2000-2020 was 0.3 ± 0.04 and 0.72 ± 0.06 respectively with a 29% increase over the period.
- The mean (2017-2020) $PM_{2.5}$ concentrations in Jaipur. (67 ± 34.6 μg/m$^{3)}$ is significantly lower compared to the capital city of New Delhi (102.6 ± 93.5 μg/m^3).
- The firecracker ban in Jaipur during 2020 Diwali was effective in keeping the pollution levels in check whereas a significantly elevated level of pollution was found during the previous Diwali festivals.
- The three regulatory monitors in the city consistently measured similar $PM_{2.5}$ values during Diwali, demonstrating very little spatial variability.
- Smoke aerosol transport from crop-fires in Northern India to Jaipur was observed in satellite data and elevated both column (i.e. AOD) and surface ($PM_{2.5}$) pollution levels on 10th November, 2020. The AOD increased by 813 % and $PM_{2.5}$ increased by 111% between 6th November and 10th November, 2020.
- Mobile monitoring in different parts of the city also did not show any spike in $PM_{2.5}$ concentrations during Diwali.
- Mobile monitoring was able to identify a pollution hotspot near an under-construction flyover in the city.

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Table 1. Mean $PM_{2.5} \pm \sigma$ (μg/m3) value of 3-Days Pre and Post Diwali for years 2017-20.

Diwali Week Days	Pre-Diwali Days			Diwali Day	Post-Diwali Days		
	-3	-2	-1		+1	+2	+3
Year							
2017	140 ± 86	145 ± 59	158 ± 41	245 ± 231	172 ± 188	195 ± 173	131 ± 66
2018	113 ± 59	63 ± 34	114 ± 49	114 ± 136	136 ± 130	171 ± 109	166 ± 127
2019	77 ± 28	110 ± 26	83 ± 30	128 ± 174	226 ± 224	222 ± 154	80 ± 32
2020	113 ± 36	88 ± 33	110 ± 36	106 ± 37	79 ± 15	63 ± 15	56 ± 18

Table 2. Mean $PM_{2.5} \pm \sigma$ ($\mu g/m^3$) value observed by performing mobile monitoring on 3 different Paths (A, B, C) of Jaipur during 2020 Diwali week.

Date & Time	11/11 (8:39am - 9:06am)	13/11 (9:15am - 10:10am)	13/11 (9:02pm - 9:50pm)	14/11 (4:07pm - 4:41pm)	15/11 (12:02am - 12:37am)	15/11 (11:30am - 12:30pm)	16/11 (6:45am - 9:40am)
Path Travelled	A	B1	B2	B3	B4	B5	C
Mean $PM_{2.5} \pm \sigma$	238.8 ± 53.6	115.3 ± 31.2	196.5 ± 34.4	93.4 ± 15.6	92.3 ± 9.6	123 ± 19.7	92.2 ± 31.5
Distance Covered (km)	8.63	11.97	13.14	12	13.9	15.3	33.1
Duration of Monitoring (Minutes)	27	33	48	34	27	37	59
Reference Monitor 24-hr mean $PM_{2.5}$	113 ± 36	110 ± 36	-	106 ± 37	-	79 ± 15	63 ± 15

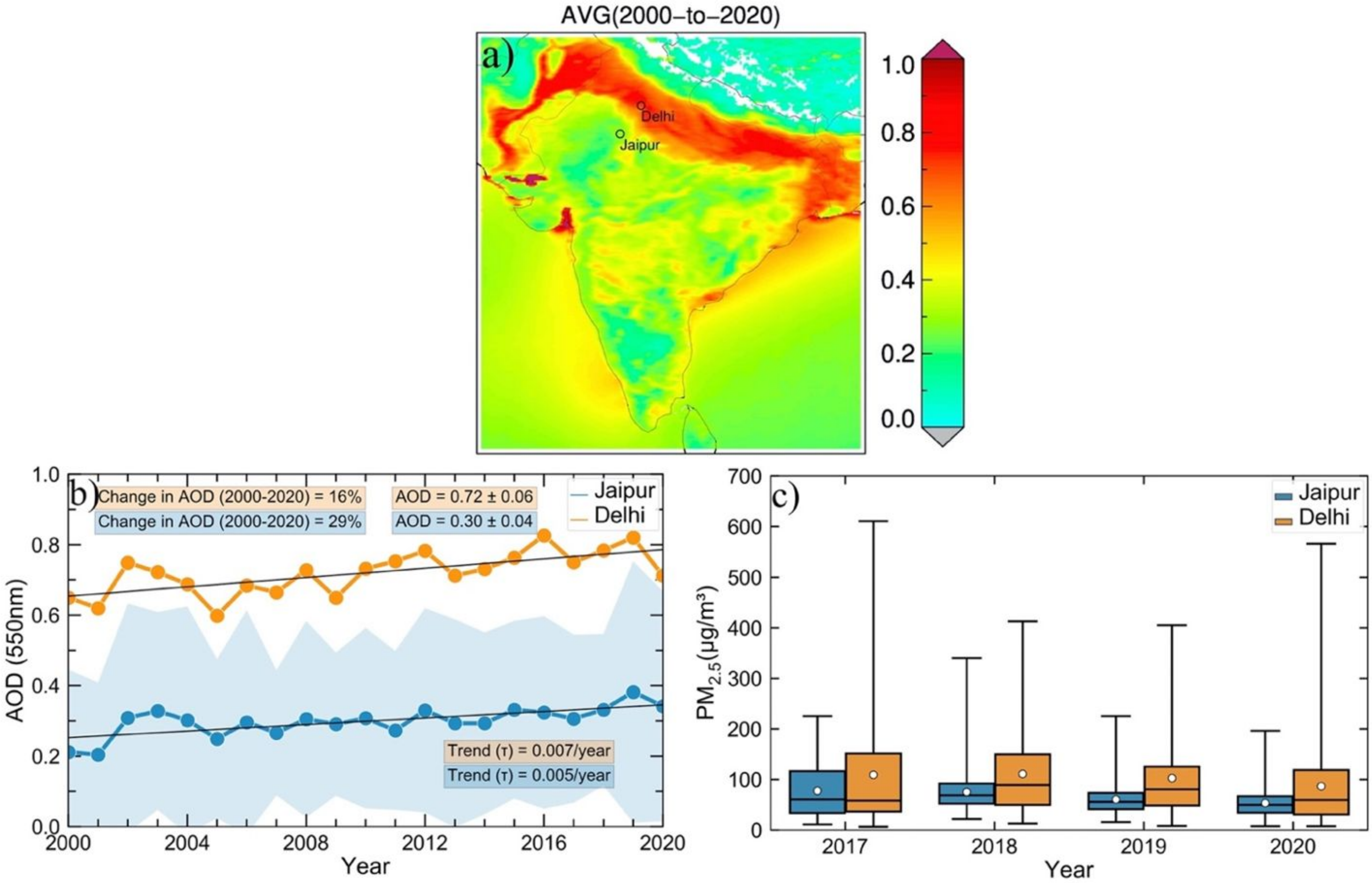

Fig. 1. a) Mean aerosol optical depth (2000-2020) derived from two MODIS sensors over India. The marked is location of Delhi and Jaipur, b) Trends in AODs over the same period for two cities extracted using same data sets; shaded area shows one standard deviation over Jaipur, c) Annual mean $PM_{2.5}$ trends (2017-2020) in two cities (Station name – Jaipur : Police Commissionerate ; Delhi : Mandir Marg).

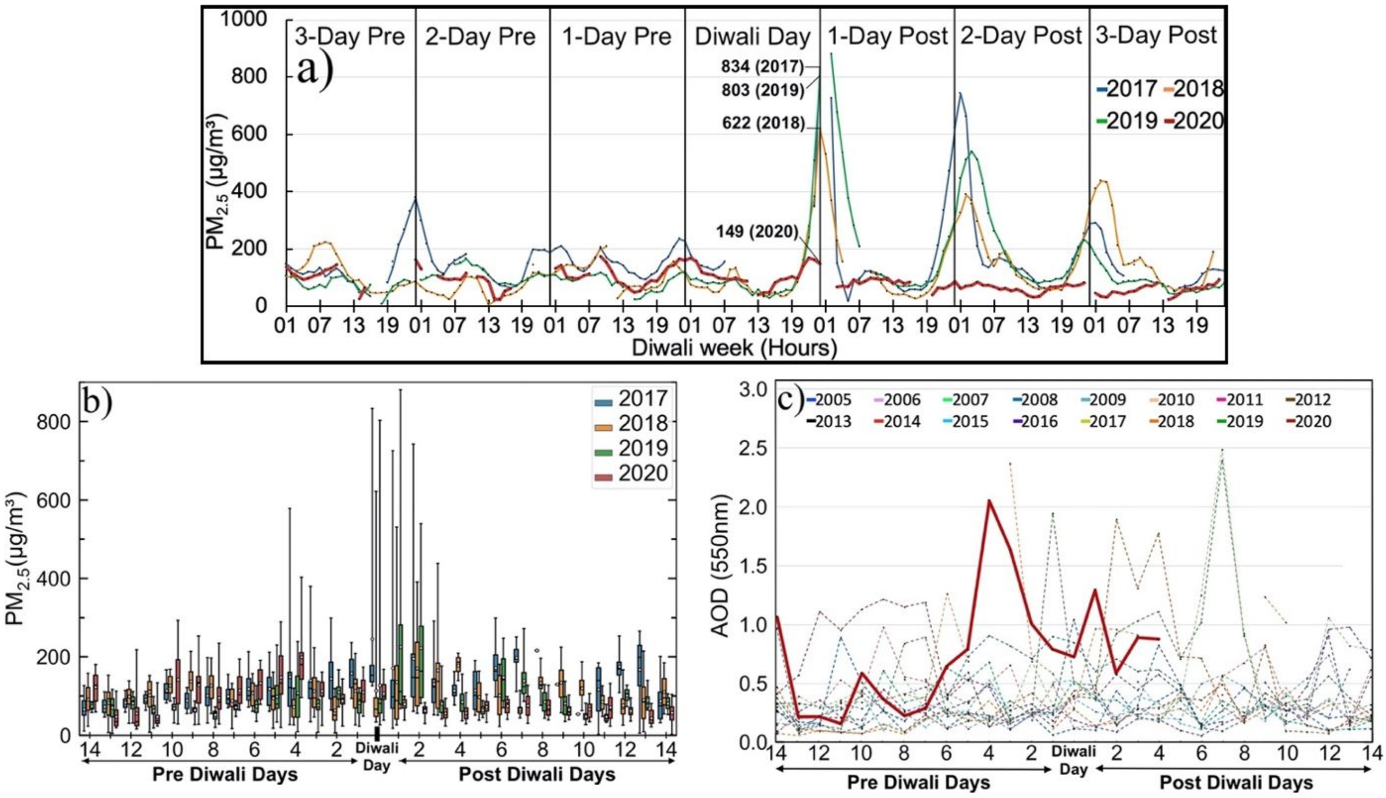

Fig. 2. a) Reference Monitor 1-hour mean $PM_{2.5}$ data of 3-Days Pre and Post Diwali for years 2017-20, hours are in local Indian standard time, b) Reference Monitor Box-Plot using 1-hour mean $PM_{2.5}$ data of 14-Days Pre and Post Diwali for years 2017-20, c) MODIS AOD data of 14-Days Pre and Post Diwali for years 2005-2020.

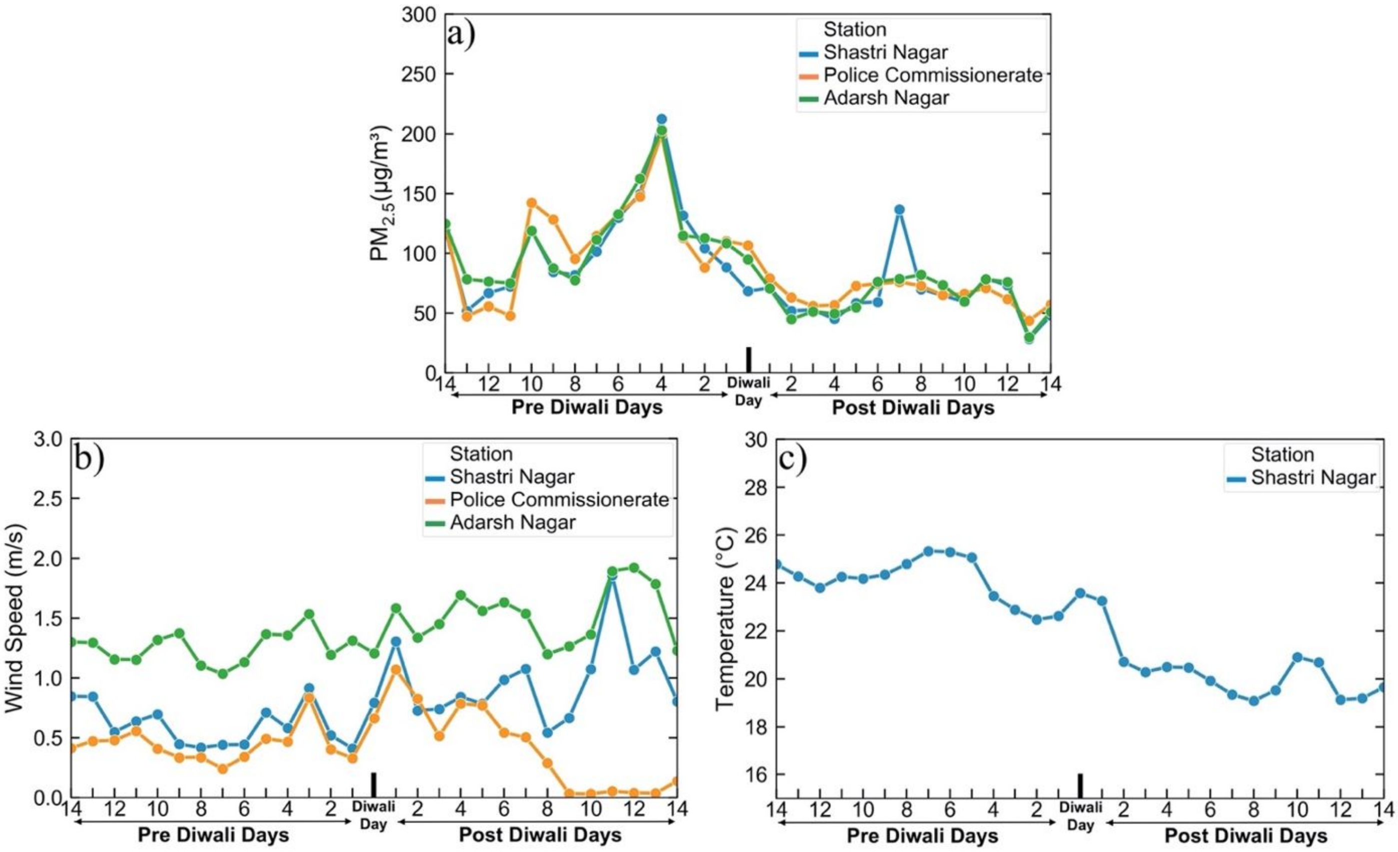

Fig. 3. Daily mean evolution of a) $PM_{2.5}$, b) Wind Speed, c) Temperature observed in Jaipur's 3-Reference Monitor for +-14 days of 2020 Diwali Week.

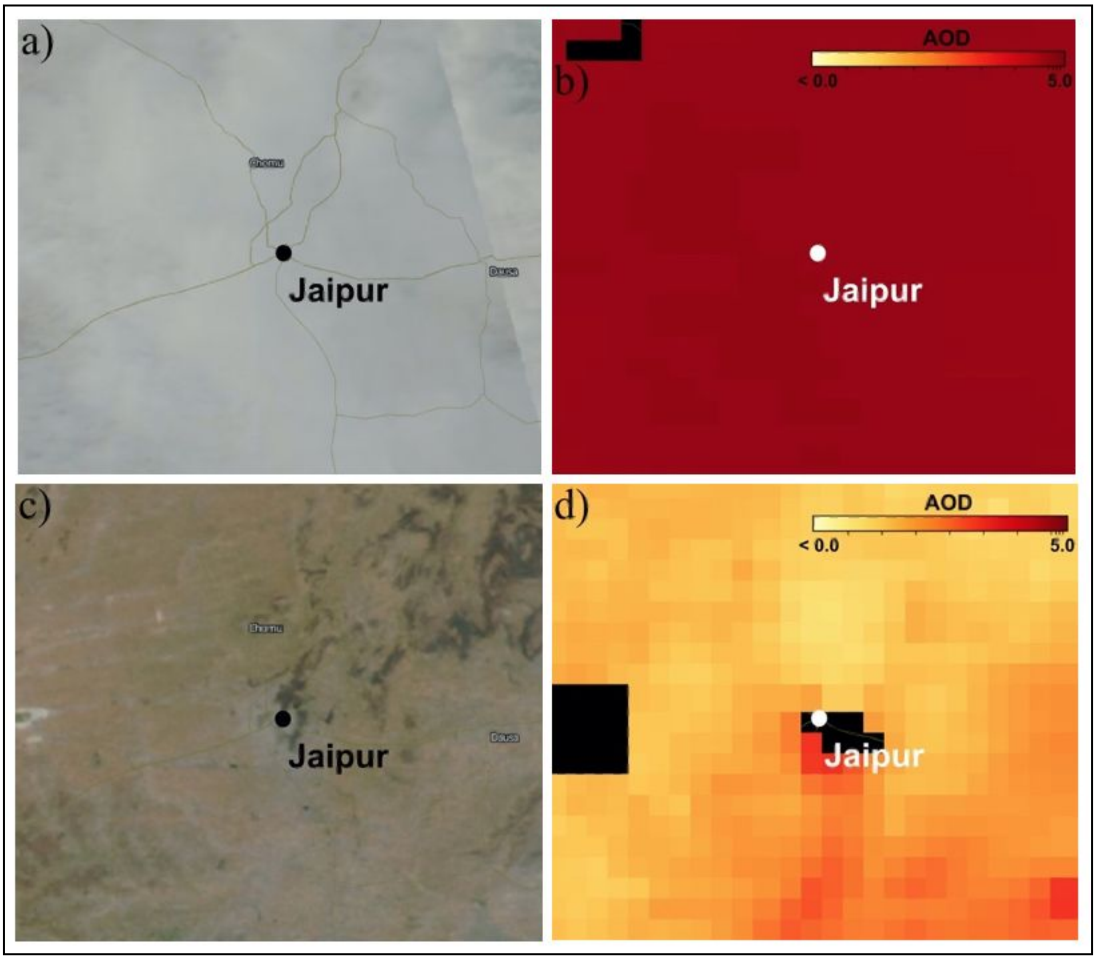

Fig. 4. Impact of aerosol transport over Jaipur during 2020 Diwali week observed from VIIRS sensor. a) shows Corrected Reflectance (True Color) and b) shows Deep Blue Aerosol Optical Thickness over Jaipur on 10/11/2020 (4th day Pre-Diwali) ; c) shows Corrected Reflectance (True Color) and d) shows Deep Blue Aerosol Optical Thickness over Jaipur on 27/11/2020 (13th day Post-Diwali).

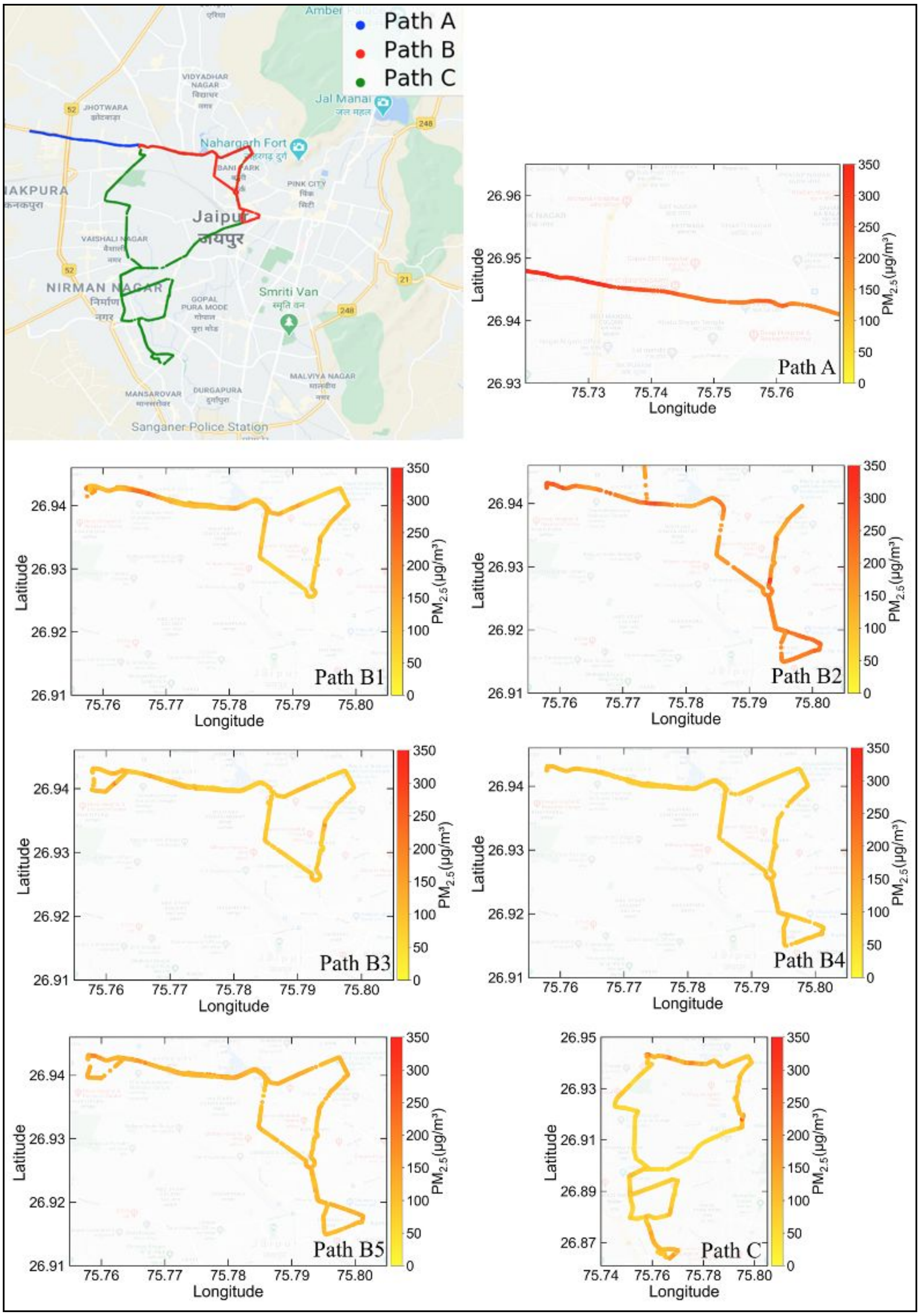

Fig. 5. Mobile air quality monitoring performed on 3 different Paths (A, B, C) of Jaipur by integrating air quality sensor on the roof of a car . Data collected from - Path A on 11/11 ; Path B1 and Path B2 on 13/11 ; Path B3 and Path B4 on 14/11 ; Path B5 on 15/11 ; Path C on 16/11.

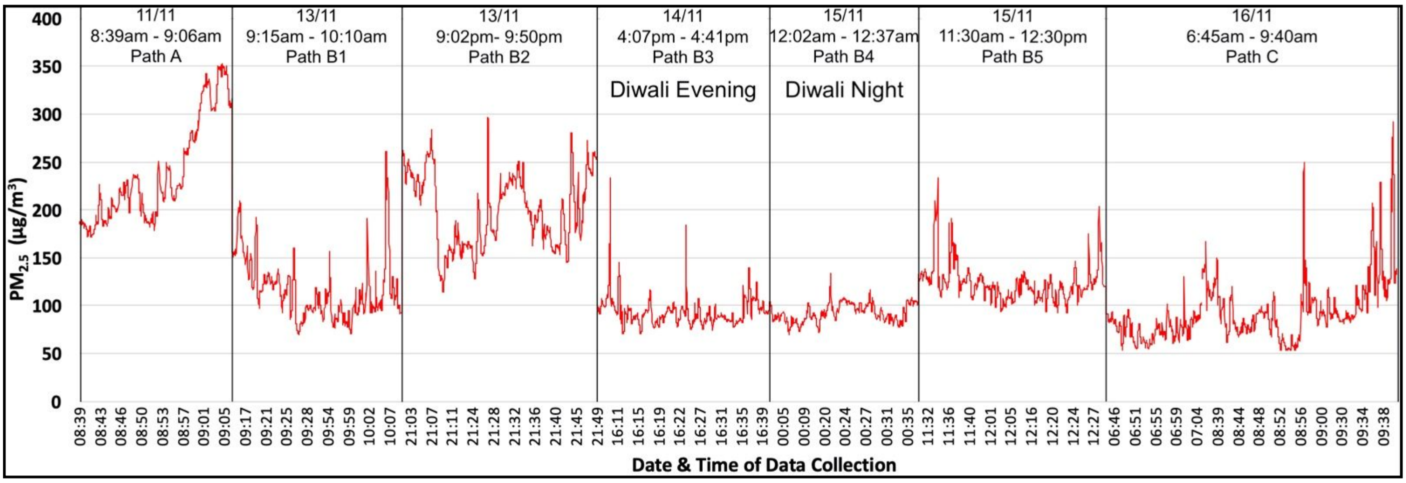

Fig. 6. Time-series plot of $PM_{2.5}$ concentrations observed by performing mobile monitoring on 3 different Paths (A, B, C) of Jaipur during 2020 Diwali week.

Supplement Material

Paper Title: Temporal and Spatial Variability in Particulate Matter Pollution in The Pink City during the 2020 Diwali Festival

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Supplement Table

Table S1. Diwali dates for the past 15 years

Year	Diwali Date
2005	01-Nov-05
2006	21-Oct-06
2007	09-Nov-07
2008	28-Oct-08
2009	17-Oct-09
2010	05-Nov-10
2011	26-Oct-11
2012	13-Nov-12
2013	03-Nov-13
2014	23-Oct-14
2015	11-Nov-15
2016	30-Oct-16
2017	19-Oct-17
2018	07-Nov-18
2019	27-Oct-19
2020	14-Nov-20

Table S2. Peak hourly PM2.5 (μg/m3) values observed during the nighttime of 2-Days Pre and Post Diwali for years 2017-20

Diwali Week Days	Pre-Diwali Days		Diwali Day	Post-Diwali Days	
	-2	-1		+1	+2
Year					
2017	210	237	834	743	291
2018	145	156	622	391	438
2019	114	121	881	540	232
2020	143	168	149	87	82

Supplement Figure

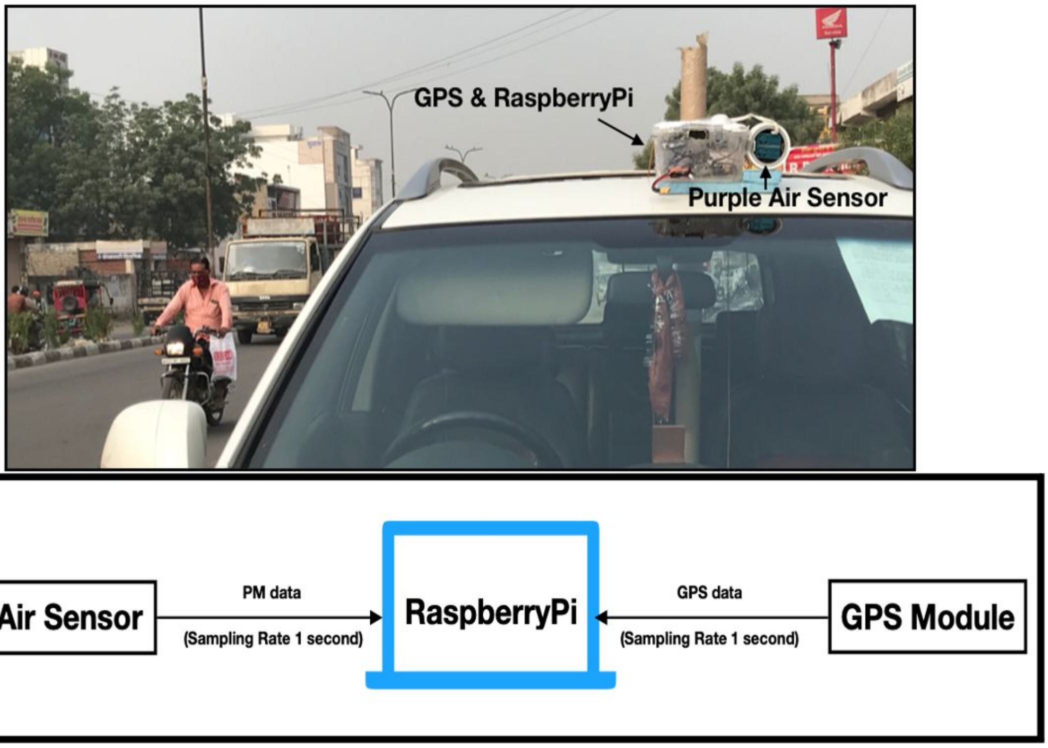

Fig. S1. Purple Air Sensor used for mobile monitoring placed on top of the car.

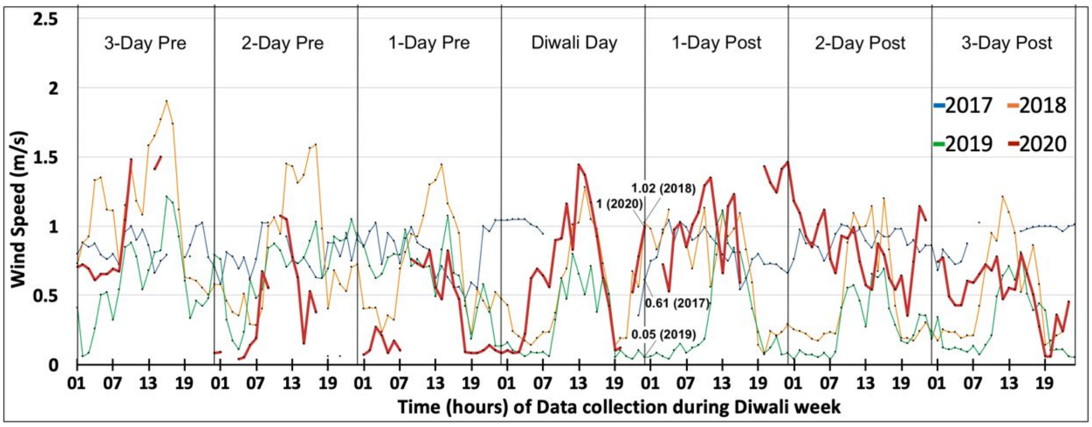

Fig. S2. Reference Monitor 1-hour mean wind speed (m/s) data of 3-Days Pre and Post Diwali for years 2017-20, hours are in local Indian standard time.

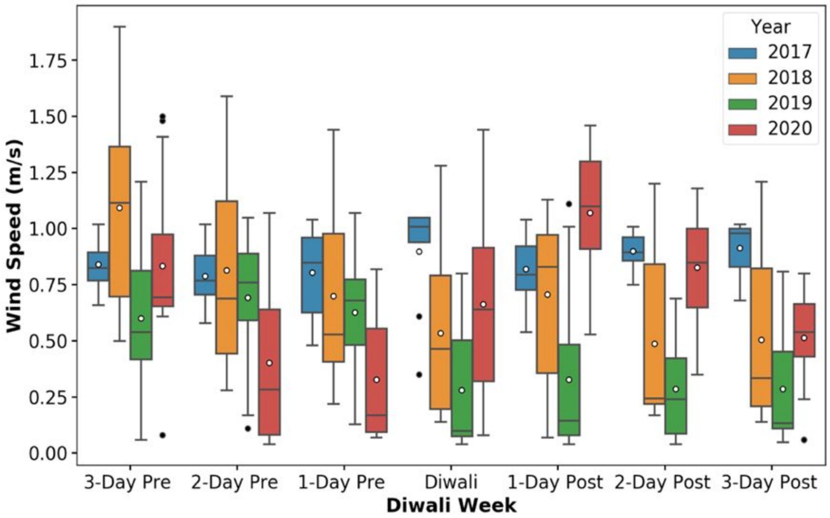

Fig. S3. Reference Monitor Box-Plot using 1-hour mean wind speed (m/s) data of 3-Days Pre and Post Diwali for years 2017-20.

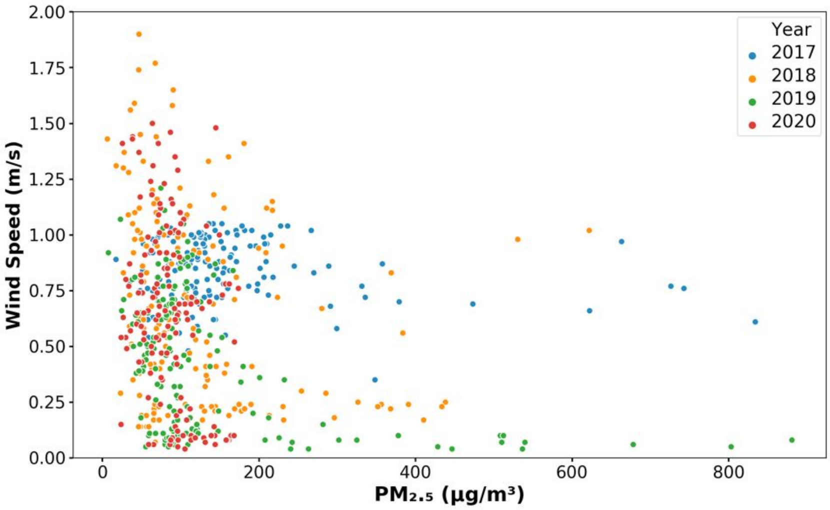

Fig. S4. Reference Monitor scatter plot using 1-hour mean wind speed (m/s) and $PM_{2.5}$ (μg/m3) data of 3-Days Pre and Post Diwali for years 2017-20.

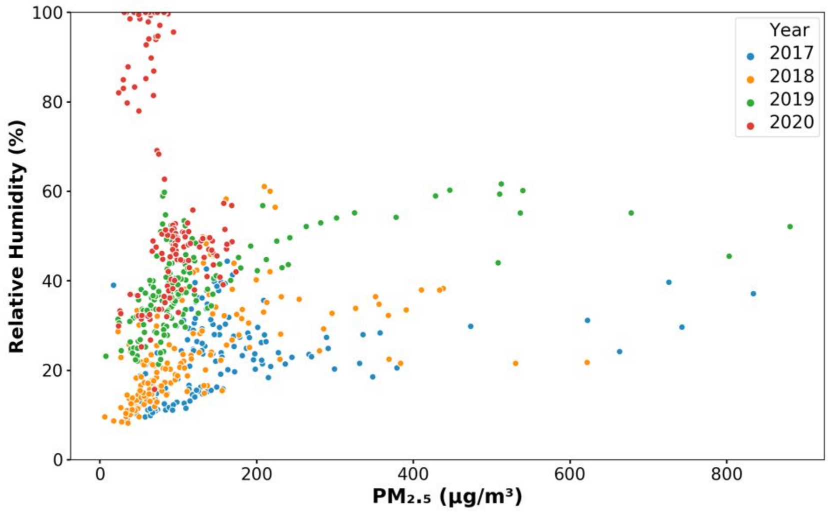

Fig. S5. Reference Monitor scatter plot using 1-hour mean relative humidity (%) and $PM_{2.5}$ (µg/m3) data of 3-Days Pre and Post Diwali for years 2017-20.

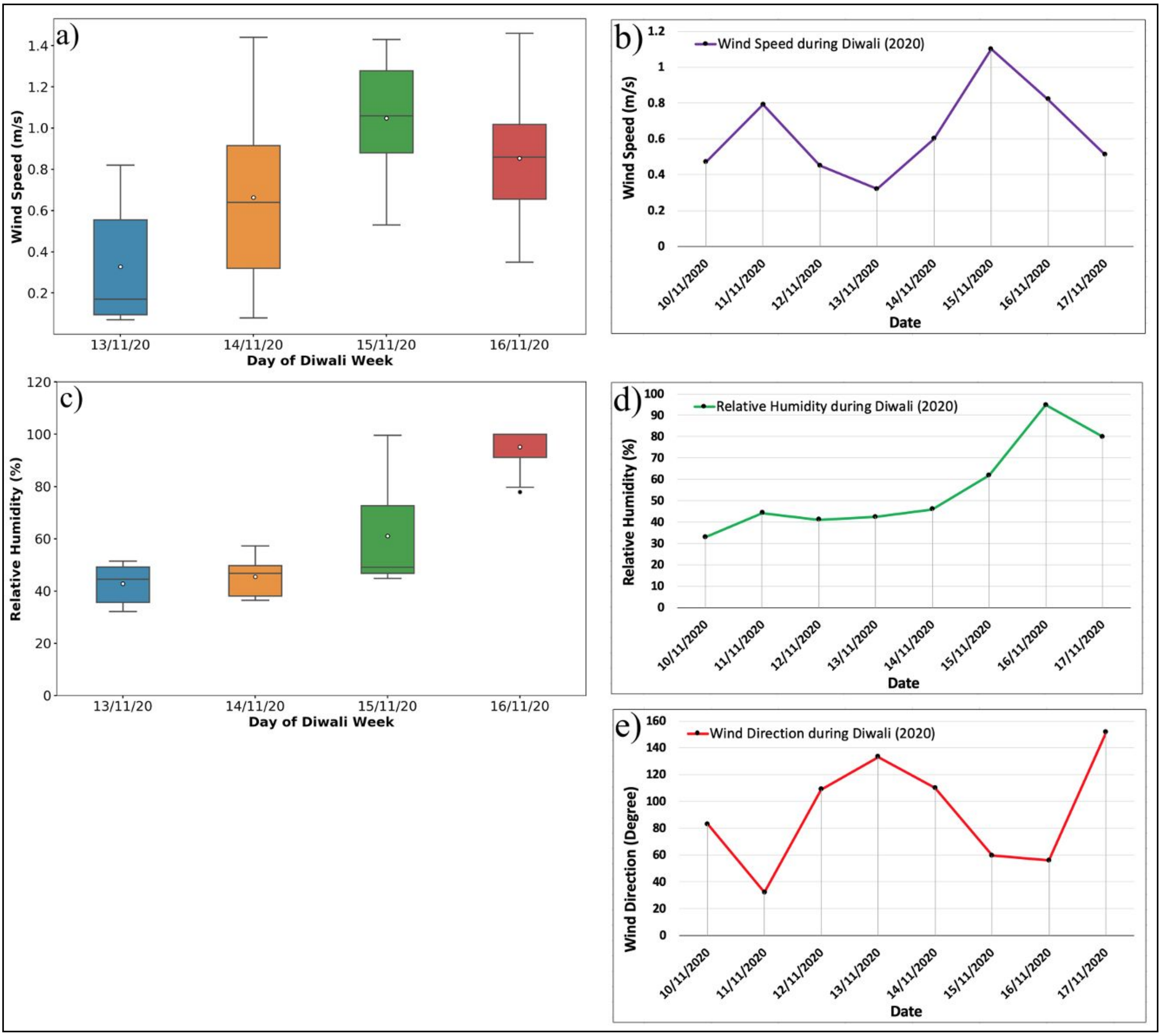

Fig. S6. a) Reference Monitor box plot using 1-hour mean wind speed (m/s) data during 4 days of 2020 Diwali week, b) Reference Monitor line plot using 1-hour mean wind speed (m/s) data during 8 days of 2020 Diwali week, c) Reference Monitor box plot using 1-hour mean relative humidity (%) data during 4 days of 2020 Diwali week, d) Reference Monitor line plot using 1-hour mean relative humidity (%) data during 8 days of 2020 Diwali week, e) Reference Monitor line plot using 1-hour mean wind direction (degree) data during 8 days of 2020 Diwali week.

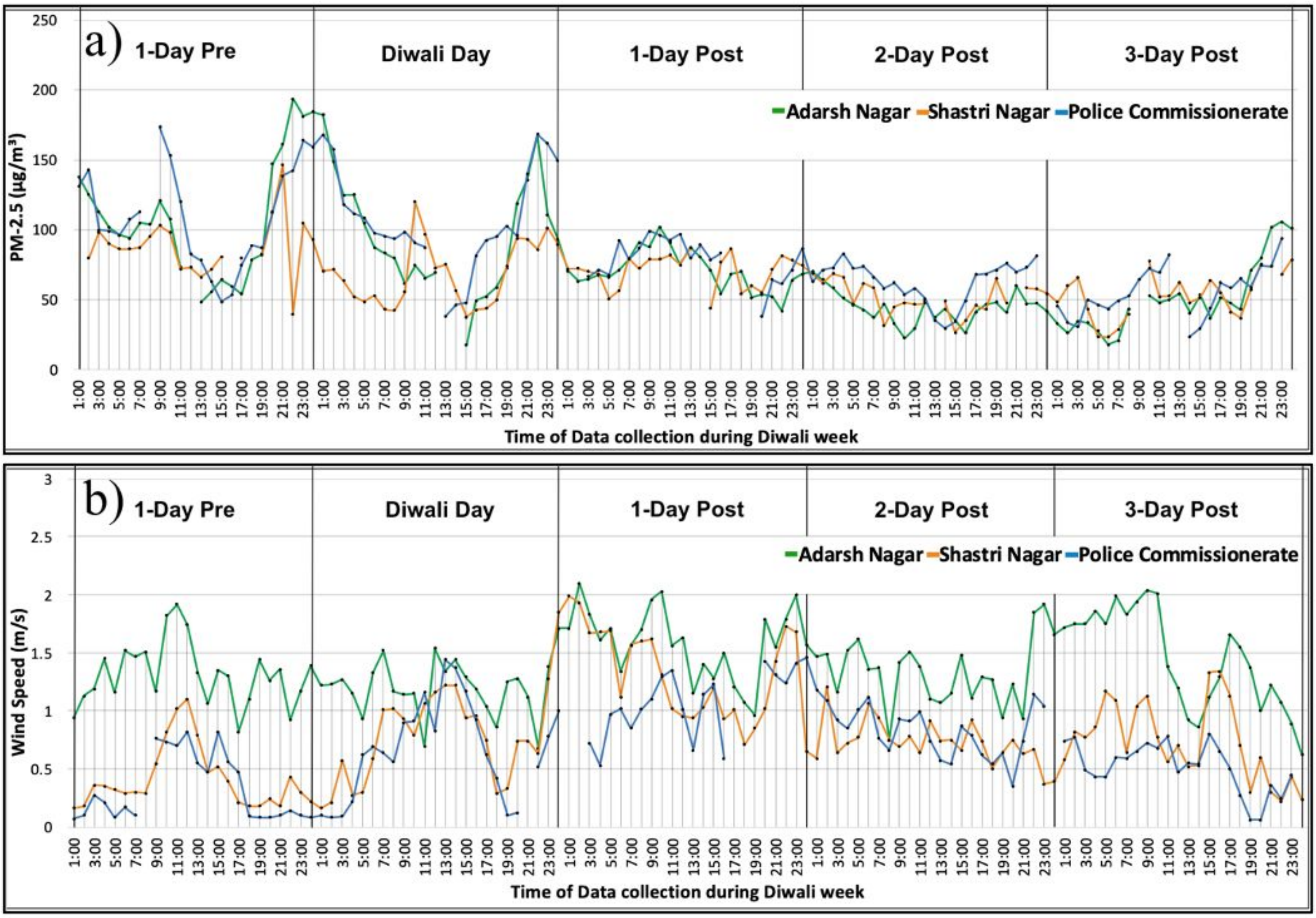

Fig. S7. 1-hour mean a) $PM_{2.5}$ (µg/m3), b) wind speed (m/s) data of the 5 day period during Diwali of the 3-different reference monitor of Jaipur, hours are in local Indian standard time.

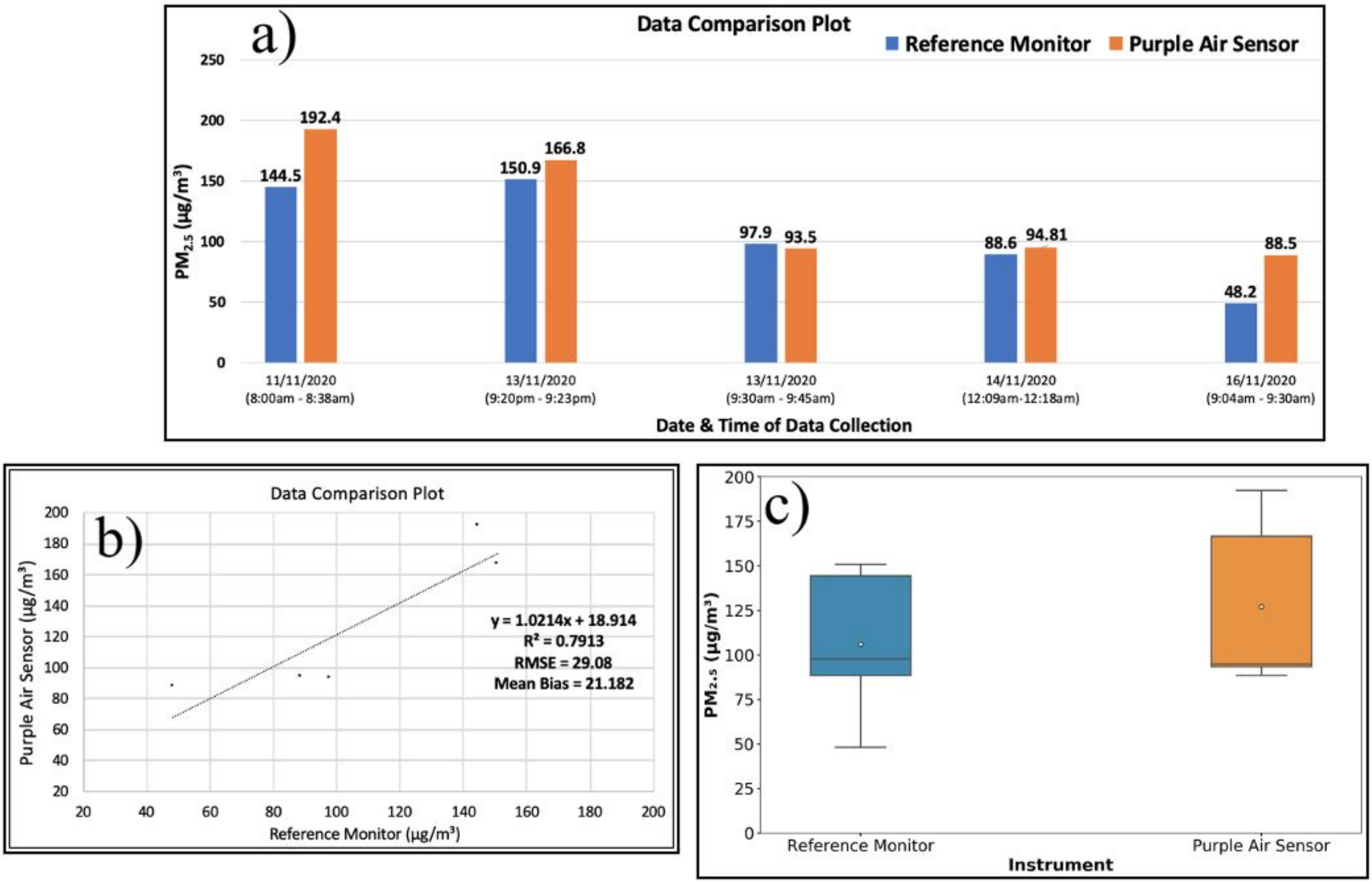

Fig. S8. Purple Air sensor data collocation results against a reference monitor (Shastri Nagar station) in Jaipur. a) Bar Plot, b) Line Plot, c) Box Plot

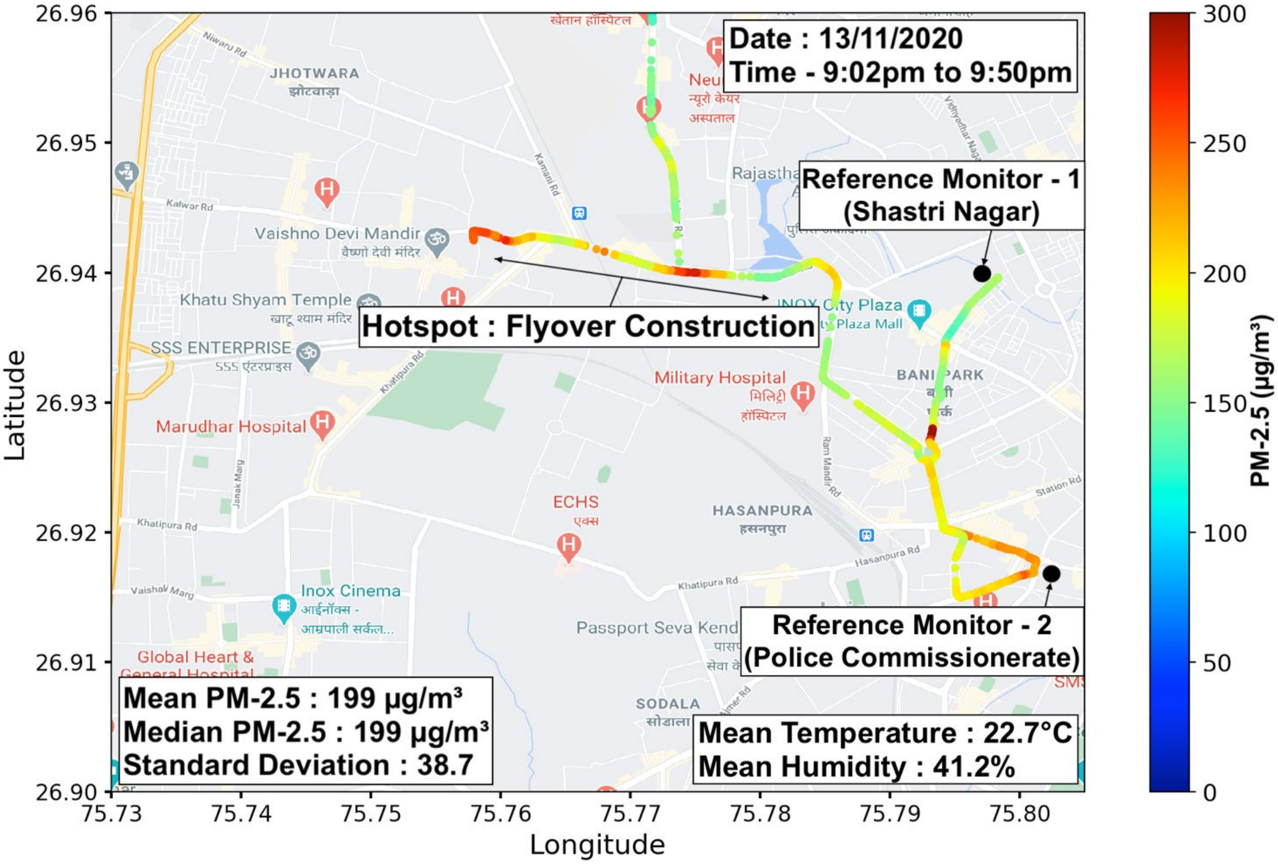

Fig. S9. Hotspot (construction site of a flyover) located by mobile monitoring experiment.