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Increasing Potential for Air Pollution over Megacity New Delhi: A Study Based on 2016 Diwali Episode

Tanmoy Mukherjee, Acharya Asutosh, Satyendra K. Pandey, Lian Yang, Partha P. Gogoi, Annu Panwar, V. Vinoj*

School of Earth, Ocean and Climate Sciences, Indian Institute of Technology Bhubaneswar, Bhubaneswar 752050, India

ABSTRACT

Air pollution over the megacity New Delhi has gained significant attention in recent times. Local pollution, along with advection from upwind sources, long-range transport and festivities (e.g., Diwali) contributing large emissions from firecrackers, has led to high loading conditions over the city. In this study, we assess a particulate pollutant event that coincided with the festival of Diwali in 2016 using multiple parameters related to particulate pollution from the ground and satellite based measurements in relation to the observed climatology during the period of 2000 to 2016. Our analysis reveals that the episode of severe air pollution in 2016 was exacerbated by the long-range transport of absorbing fine aerosols emanating from biomass/stubble burning in the adjacent states to the northwest of National Capital Territory (NCT) of India. Based on concentration weighted trajectory (CWT) analysis using the $PM_{2.5}$ mass concentration and AOD, the high loading conditions were related to trajectories that passed through the northwest of NCT. The period after Diwali in 2016 also coincided with air masses traversing large biomass burning areas. The long-term changes in the fire counts indicate that these events have been increasing at an alarming rate of ~25% per year since 2000, creating the potential for high particulate pollution over downwind cities such as Delhi.

Keywords: Urban air pollution; Delhi; Diwali, $PM_{2.5}$; Aerosols; Biomass burning.

INTRODUCTION

The degradation of air quality and frequent heavy pollution events in urban agglomerations have become a major concern in the recent times. New Delhi, the capital city of India and the fifth most populous city in the world, was declared as one of the most polluted cities in the world (World Health Organization, 2016). In addition, it was also reported that 13 of the 20 most polluted cities were in India. Concentrations of regulated air pollutants often exceed the National Ambient Air Quality Standards (NAAQS). Recent studies show that $PM_{2.5}$ exceeded NAAQS during 85% of the days in a year. This being 95% during the winter and 68% during monsoon (Sahu and Kota, 2017). The rapid urbanization in Delhi has also resulted in increased atmospheric concentration of air pollutants, which is a major threat to the public health (Guttikunda and Goel, 2013). Past studies which monitor and analyze the aerosol and particulate matter concentrations (Mitra and Sharma, 2002; Srivastava and Jain, 2007; Tiwari *et al.*, 2013; Sahu and Kota, 2017) have all highlighted the critical nature of air quality situation over the city. The particulate matter in particularly the $PM_{2.5}$ is co-emitted along with many other pollutants and has been widely used as a proxy for air pollution. The continuous increase of $PM_{2.5}$ in Delhi (Biswas *et al.*, 2011) indicates potential worsening of air quality in the future. Few investigations have confirmed that aerosol concentrations remain high throughout the year in Delhi (Srivastava and Jain, 2007; Mohan and Payra, 2009) which exceeds the national ambient air quality standards (Sharma *et al.*, 2013). Using Greenhouse Gases and Air Pollution Interactions and Synergies (GAINS) model, Dholakia *et al.* (2013) concluded that critical air quality situation will continue into the future (even into 2030), unless appropriate emission controls are developed. Recent studies reported that several unique features like topography, long-range transport, large local emissions and festivals all attribute to high loading conditions over this region (Ghosh *et al.*, 2015; Sahu and Kota, 2017).

Diwali or the Festival of Lights is considered as one of the biggest festivals in India, which is celebrated throughout the country during post-monsoon period every year. The celebration is associated with combustion of a large quantity of fireworks, which contributes to notable amount of carbon monoxide, nitrogen dioxide, ozone, particulate matter (PM), sulfur dioxide, lead and various other pollutants to the atmosphere. Several studies have been carried out on air

* Corresponding author.
E-mail address: vinoj@iitbbs.ac.in

pollution events during Diwali festival across the country (Ravindra *et al.*, 2003; Ganguly, 2009; Chatterjee *et al.*, 2013; Chauhan *et al.*, 2014; Bhatnagar and Dadhich, 2015; Nasir and Brahmaiah, 2015; Nigam *et al.*, 2016). Most of these studies show the impact of Diwali festival to the elevated concentrations of particulate matters and other pollutants in ambient air in comparison with the pre-festival days. Though the air pollution levels are mostly high over Delhi, events like Diwali accentuates severe air pollution episodes. Despite causing air quality degradation during Diwali each year, some years' experience critical pollution episodes during and after Diwali event. For example, the city experienced one of the most acute episodes of air pollution in the recent times starting 30 October 2016 for over a week causing widespread unease to the public. This specific occurrence of high pollution episode during Diwali prompted this investigation into the potential causes for the occurrence of this high pollution event.

DATA AND METHODOLOGY

Atmospheric remote sensing provides a unique opportunity to compute indirect estimates of air quality (Kumar *et al.*, 2007; Weber *et al.*, 2010; Dey *et al.*, 2012). Furthermore, these are essentially important for the management and surveillance of air quality in megacities of developing countries. Multiple satellite-derived parameters along with ground based $PM_{2.5}$ mass concentrations have been used. Aerosol Optical Depth (AOD) from MODIS (Moderate Resolution Imaging Spectroradiometer) (Terra platform) at a resolution of 1 × 1 degree is used. This dataset has been widely used globally as a proxy for $PM_{2.5}$ mass concentration (van Donkelaar *et al.*, 2006) or are used as a primary input for retrieval of $PM_{2.5}$ using different techniques. MODIS AOD retrievals have been found to be of reasonable accuracy over the Indian region (Prasad *et al.*, 2004; Tripathi *et al.*, 2005) and is found to be of high quality with sufficiently long-term operation (Jethva *et al.*, 2007; Dey and Di Girolamo, 2011). Along with AOD, Angstrom Exponent (AE) ($alpha_{412\text{-}470}$) is also used to investigate the particulate/aerosol size distribution. Absorption Aerosol Optical Depth (AAOD) and UV Aerosol Index (UVAI) are used to distinguish contributions from absorbing aerosols. More details of the dataset are provided in Table 1. UV Aerosol Index act as an indicator detecting the presence of absorbing aerosols such as dust or soot. The detection is based on spherical contrast method in a UV field where UV absorption by ozone is negligible. The higher value of UVAI detects dust or smoke while lower values indicates the presence of non-absorbing aerosols (Herman *et al.*, 1997). UV Aerosol Index can clearly distinguish the smoke and soot particle originating from biomass burning which is consistent with the observation data (Hsu *et al.*, 1996). Daily Level-3 gridded fire count data is utilized from MODIS-Terra Collection 6 (Giglio, 2015). The Level-3 (MOD14A1) fire products are tile based 1-kilometer gridded composite packaged into 8 days per file. This product has been extensively validated using ground based and airborne sensors (de Klerk, 2008; Schroeder *et al.*, 2014). In the present study, we have used fire pixel count inside a domain (70°E to 75°E and 31°N to 35°N) adjacent to the NCT region for year 2000–2016.

Diwali pollution episode in 2016 is considered as a specific high pollution event. We here distinguish the characteristics of different parameters during 2016 with respect to the climatology. To investigate the contribution of the surrounding crop burning residue on 2016 episode, National Oceanic and Atmospheric Administration's (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) (Draxler and Hess, 1998) modeling system is used in the online mode to simulate 72-hour trajectories (backward) for 500 and 1000 m arrival heights in order to distinguish regional vs. distance potential emission sources. As backward trajectories follow Lagrangian path of air parcels, back-trajectory analysis has been carried out to discern potential source regions and possible transport pathways of pollutants. Finally, to explore the contribution of the long-range transport, we utilized the HYSPLIT trajectories to carry out the concentration-weighted trajectory (CWT) analysis, which illustrate potential sources of high aerosol loading during the period around Diwali over New Delhi (Seibert *et al.*, 1994; Hsu *et al.*, 2003; Vinoj *et al.*, 2010).

RESULTS AND DISCUSSION

Variation of AOD and $PM_{2.5}$ over Delhi

India has undergone significant economic development in the recent times. Past studies have shown that AOD is increasing at a rate of ~3% per year because of anthropogenic activities (Babu *et al.*, 2013) using long-term AOD measurements. Similar results were also reported by other studies (Kaskaoutis *et al.*, 2012; Pandey *et al.*, 2016). Due to lack of publicly available long-term AOD measurements over New Delhi, we have used AOD as a proxy for particulate pollutants to explore the trends (see

Table 1. Description of the data used for the analysis.

Parameter Name	Source	Spatial Resolution	Temporal Resolution
$PM_{2.5}$	7 stations operated by CPCB at Delhi, India	Point sources	24 hours average
Aerosol Optical Depth at 550 nm (AOD)	MODIS-Terra	1° × 1°	Daily
Angstrom Exponent (AE)	MODIS-Terra	1° × 1°	Daily
UV Aerosol Index (UVAI)	OMI	1° × 1°	Daily
Absorption AOD at 500 nm (AAOD)	OMI	1° × 1°	Daily
Fire Count	MODIS-Terra	1 km	Daily

Fig. 1) during post-monsoon season coinciding with the festival Diwali. Our analysis further shows that AOD has increased by ~54% with an annual increment of ~3.2% per year with respect to 2000.

This monotonous growth in AOD over this region indicates the increasing background aerosols loading in the recent years. This implies that Diwali events will further accentuate loading conditions through particulates/aerosols and trace gases. These increases in aerosol loading are a consequence of both natural and anthropogenic factors.

The 2016 Diwali pollution event is considered as one of the major air pollution episodes in recent times prompting even the judiciary to recommend steps to the government in the form of banning of firecrackers during 2017 Diwali. The government also introduced the odd-even scheme whereby only ~50% of the vehicles in the capital could operate on any given day. Studies have shown mixed results to these initiatives. To examine the characteristics of 2016 Diwali event, $PM_{2.5}$ mass concentration (24-hour mean from 7 sites within New Delhi) data provided by Central Pollution Control Board is used during the period 20 October 2016 to 9 November 2016 (see Fig. 2). The stations used were Anand Bihar, Dwarka, IHBAS, Mandir Marg, Punjabi Bagh, RK Puram and Shadipur all located within the Delhi NCT.

Fig. 2 shows the variability of $PM_{2.5}$ over a 21-day period around Diwali (30 October 2016). It can be seen that prior to 26 October 2016, the $PM_{2.5}$ values were ~100 µg m^{-3} (higher than the NAAQS standard of 60 µg m^{-3}). However, starting from 26th, an increase is observed to ~250 µg m^{-3} on the next day of Diwali (31 October 2016). This increasing trend then continued unabated until 2 November where there was a respite for a couple of days. However, the $PM_{2.5}$

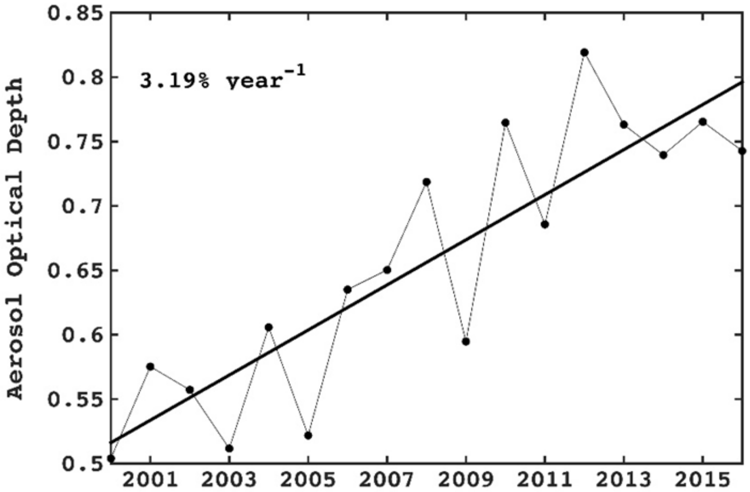

Fig. 1. Long-term trend of Aerosol Optical Depth over Delhi during October and November using MODIS Terra.

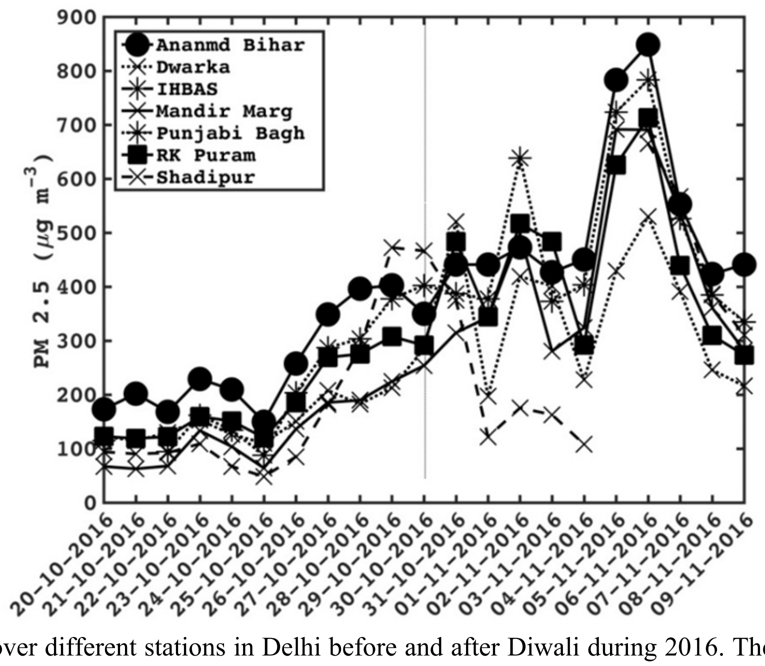

Fig. 2. $PM_{2.5}$ variability over different stations in Delhi before and after Diwali during 2016. The thin grey line shows the date of Diwali.

levels went up to a daily mean value of ~800 µg m^{-3} on 5 November, about 6 to 7 days after Diwali. It is not surprising to have high loading conditions after Diwali, however its continuation for more than a week to alarming levels is. In addition, it is found that the increasing trend started several days prior to the Diwali clearly indicating that festival emissions alone may not have caused such deterioration of air quality a week later. Having found that the high loading condition observed during 2016 is not just a consequence of festivities alone; we further explored the variability in other related parameters such as Ultra Violet Aerosol Index (UVAI), AAOD, $PM_{2.5}$ and AOD during Diwali period using 17 years of satellite measurements.

Climatological Features

We have used available satellite and ground based measurements for the period starting from year 2000 so as to ascertain how different was 2016 with respect to the climatology. It may be mentioned that the date of Diwali changes from year to year due to the use of lunar calendar. Therefore, we used the celebration date as the central point and used data for 10 days before and after for each year to see whether the average values of various parameters such as $PM_{2.5}$, AOD, UVAI and AAOD are different from 2016. It may be mentioned that changing Diwali dates makes a direct comparison between different years difficult due to the large seasonality in PM and aerosol loading characteristics over Delhi. In order to avoid these issues, we have normalized the mean value of different parameters for each day with the average of these means over the 21-day period. This method also potentially brings out whether the first or second half (before or after Diwali) were higher.

Fig. 3 shows the inter-comparison between climatological anomaly and 2016 anomaly for different parameters within a period of 10 days before and after Diwali. The central vertical line denotes the Diwali date. Each of the parameters show a clear pattern with anomalies higher after the Diwali than before. In addition, the trend during 2016 shows values higher than climatology for most days after Diwali. However, climatology for UVAI, which is sensitive to biomass burning, does not show any increase after Diwali. However, all the parameters show that 2016 year corresponds to a situation with rising pollution levels even before Diwali with higher loading persisting for over a week after Diwali. We also calculated the high (low) AOD dates within the 21 days that are higher (lower) than two sigma of the mean values for 2016. It is clear that the higher AOD's corresponds to periods after Diwali and lower AOD's before Diwali respectively. This finding is not surprising but expected. Unlike the climatology for UVAI, higher values were observed after Diwali for UVAI, which was also similar to the AAOD signifying the presence of absorbing aerosols and potentially biomass burning in nature after the Diwali events. Measurement based studies in the past have shown that Diwali effect normally subsides in a couple of days (Beig, 2016). However, all parameters show a clear high loading for over a week with potential biomass burning (absorbing aerosol) signature observed in UVAI (AAOD). In 2016, the values remained high for several days after Diwali. An analysis is carried out to quantify and to determine whether averaging periods (number of days before and after Diwali) would bias our findings.

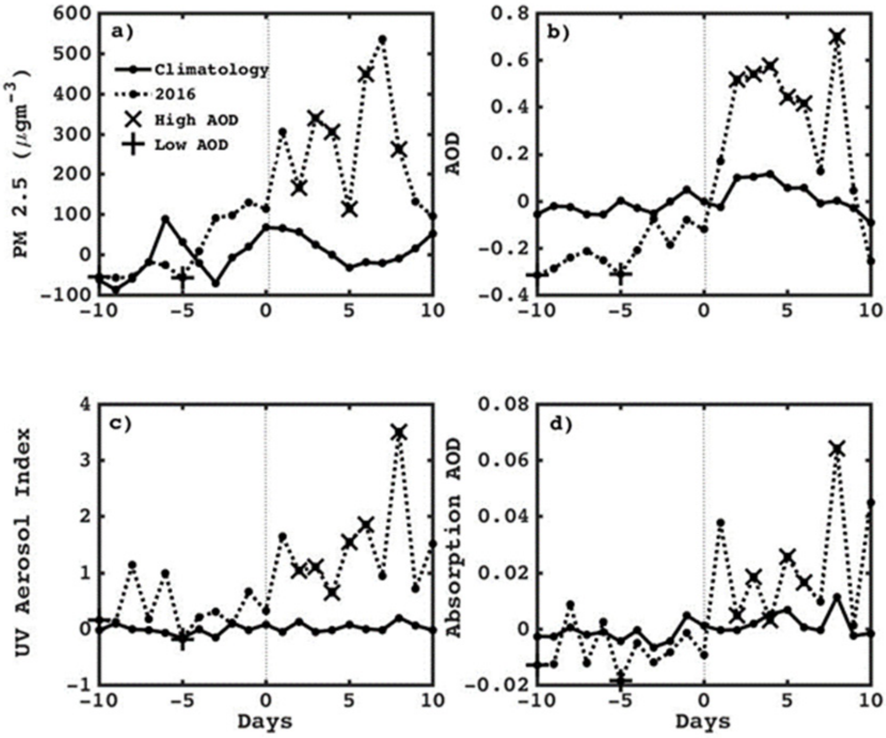

Fig. 3. Inter comparison between the climatological anomaly and 2016 anomaly of a) $PM_{2.5}$, b) Aerosol Optical Depth (AOD), c) UV Aerosol Index and, d) Absorption AOD over Delhi.

Fifteen years of climatology during pre- and post-Diwali over Delhi region were compared with the observed values during 2016 and are provided in Table 2. It is observed that on a climatological sense, $PM_{2.5}$ shows an increased loading of ~43% after Diwali (if averaging is done for 3 days). However, this decreases considerably to ~20% (if averaging is done for 10 days). This shows that $PM_{2.5}$ values are normally higher after Diwali, but they drastically fall off with time to about half within ~10 days. This may also be due to seasonality in $PM_{2.5}$ mass during this period. However, a comparison with year 2016 reveals that the average after Diwali (3 day) was ~58% higher than Diwali. However, the values observed after Diwali (10-day mean) was ~144% higher than Diwali. This is surprising when compared to the climatology that shows a decrease to half when averaged for 10 days after Diwali. This clearly shows that the major increase in $PM_{2.5}$ had occurred after 3 days of Diwali with almost more than doubling during this period. AOD, being a column measure of particulates normally shows only a nominal increase of ~5% (3-day mean) after Diwali. However, this was over 110% during 2016. Such large increases over the whole column loading is not expected from changes to local emissions alone. This further increased to ~150% with respect to Diwali when a 10-day period is used. This again suggests that particulate loading increased at a faster rate after Diwali not only because of Diwali induced firecracker related activities alone. Similar results were obtained for UVAI and AAOD as well with increases (in percentages) that are a factor of ~20 which is impossible based on only emissions related to Diwali alone. In fact, climatological variation of UVAI during this period shows a decrease, implying a decreasing role of biomass burning during Diwali period depending on the dates. This is also consistent with the MODIS fire counts. However, as the location of biomass burning is not the same as that of $PM_{2.5}$ measurement, there is a time lag between the high fire counts and high loading conditions over Diwali. This may be due to time taken for the transport of biomass burning related aerosols over to the city. It may also be noted that the fire counts were almost 70% (20%) larger in 2016 during 3 days (10 days) before Diwali in comparison to the climatology. Most of the biomass had been burnt before Diwali leading to the delayed accumulation/advection of associated absorbing aerosol loading over Delhi. All these points to the possibility of advection of biomass burning induced aerosol loading over New Delhi after the Diwali event. The large difference between the climatological figures with respect to 2016 shows that the Diwali celebration itself could have only a small impact on the overall loading of the aerosols/particulates.

Long-Term Variation of the Pollution Parameters

In this section, we have further investigated the long-term variation of different parameters over New Delhi. A total of 17 years of daily satellite Level-3 data were utilized. However, $PM_{2.5}$ data were only available from 2012 from CPCB. We have calculated average values for the twenty days period before and after Diwali and the average during this whole period.

We find that except AAOD, all parameters show an increasing trend albeit the large inter-annual variation. The increase in AOD is not surprising. However, the increase in UVAI points to increased vegetation related burning and hence aerosol loading. As was observed earlier, Fig. 4(c) shows clearly that UVAI after Diwali was clearly larger than before Diwali. However, most years show that the UVAI is lower after Diwali.

The above analysis reveals that 2016 had a high peak in $PM_{2.5}$, AAOD and UVAI, but AOD was slightly lower than 2015. However, a careful analysis reveals that AOD after Diwali was higher by a factor of ~2 during 2016 in comparison to before Diwali. This clearly indicates that all parameters show an increase with time with days after Diwali during 2016 being higher in comparison to previous

Table 2. Comparative analysis of a) $PM_{2.5}$, b) AOD, c) AE, d) UVAI and, e) Fire Counts with respect to climatology and 2016 pollution episode.

Parameter	Climatology (2000–2015)					
	Mean ± Std				Percentage Change (%) w.r.t pre Diwali	
	Before Diwali		After Diwali			
	10 days	3 days	10 days	3 days	10 days	3 days
*$PM_{2.5}$	158.81 ± 54.39	157.97 ± 45.83	190.33 ± 35.36	225.97 ± 21.40	19.84	43.05
AOD	0.56 ± 0.03	0.58 ± 0.05	0.58 ± 0.06	0.61 ± 0.06	3.54	5.38
AE	0.95 ± 0.11	1.03 ± 0.10	1.09 ± 0.10	1.05 ± 0.08	15.03	1.64
UVAI	1.25 ± 0.10	1.26 ± 0.15	1.23 ± 0.08	1.23 ± 0.13	–1.80	–2.11
AAOD	0.0313 ± 0.003	0.0311 ± 0.01	0.0330 ± 0.004	0.0314 ± 0.006	5.46	0.97
Fire Count	99.38 ± 30.64	101.59 ± 22.30	70.47 ± 26.30	83.85 ± 37.67	–29.09	–17.46
Year 2016 Only						
$PM_{2.5}$	183.26 ± 73.39	284.16 ± 20.72	448.26 ± 146.75	448.36 ± 91.59	**144.61**	**57.79**
AOD	0.36 ± 0.09	0.46 ± 0.06	0.9 ± 0.30	0.98 ± 0.21	**153.50**	**114.22**
AE	1.15 ± 0.17	1.22 ± 0.21	1.14 ± 0.40	1.39 ± 0.27	–1.16	**14.14**
UVAI	1.67 ± 0.42	1.65 ± 0.15	2.76 ± 0.83	2.57 ± 0.13	**64.95**	**55.11**
AAOD	0.0256 ± 0.01	0.0256 ± 0.005	0.0533 ± 0.027	0.0531 ± 0.017	**116.36**	**107.72**
Fire Count	119 ± 95.06	169.67 ± 110.46	70.6 ± 125.96	37.67 ± 53.58	–40.67	–77.80

*$PM_{2.5}$ values are available from 2011.

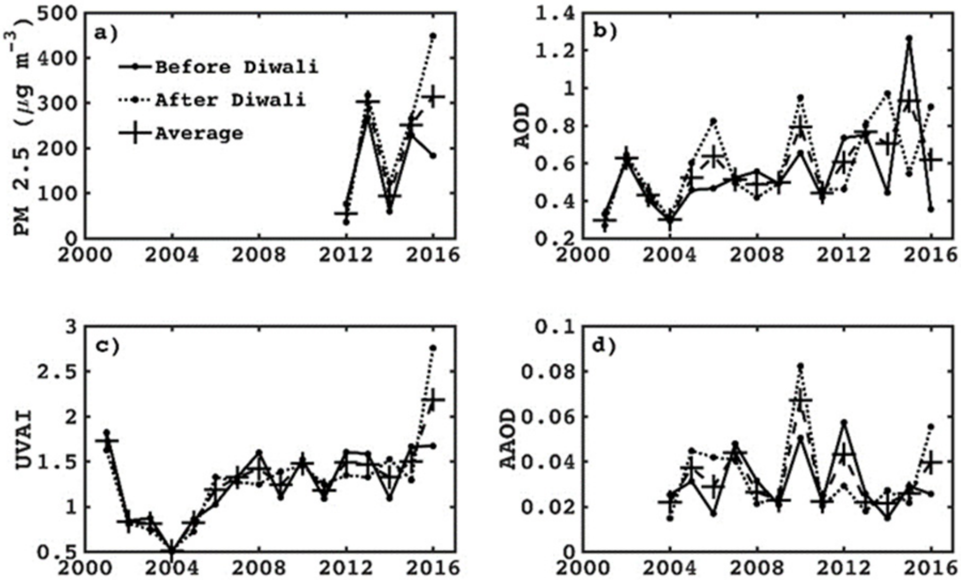

Fig. 4. Comparison between the long-term variation of a) $PM_{2.5}$, b) Aerosol Optical Depth, c) UV Aerosol Index and, d) Absorption AOD before, after and in Diwali dates over Delhi.

years. This is consistent with our analysis based on climatological means. Past studies have shown that particulate matter concentrations were higher during Diwali in comparison to pre- or post-Diwali days in various cities of India (Chauhan *et al.*, 2014; Verma and Deshmukh, 2014). Our study shows that the post-Diwali days during 2016 were higher than both Diwali and pre-Diwali days. The above analysis reveals that regular activities on local scale cannot fully explain the severe air quality episode that happened during 2016. Also, the background concentrations over the Delhi region is increasing mostly as a consequence of local anthropogenic activities and also increased vegetation related burning upwind as observed in UVAI and also fire counts. The above analysis suggests that 2016 pollution levels were much higher than those observed in the past and had persisted for over a week longer than normal and started the increasing trend much before Diwali. This prompted us to explore the possibility of a remote effect through long-range transport in leading to an increased particulate loading over Delhi during 2016. In order to explore the possibility of long-range transport, we used air mass back trajectory analysis using HYSPLIT to understand the high loading conditions over Delhi region. The details are provided in the next section.

Role of Long-range Transport

To identify the effect of long-range transport over the study region and also identify the spatial pattern of the potential areas which could modulate the aerosol loading condition over Delhi, we used the widely used concentration weighted trajectory (CWT) analysis using trajectories associated with every 6 hours during the 21 days inclusive of Diwali day for the 17 years considered since 2000. CWT analysis provides weighted trajectories on the basis of mean concentration of any parameter (like $PM_{2.5}$) at a particular site with the arrival of trajectory at that point. With the crossover of the associated trajectory, each grid point obtains a weighted concentration by averaging the concentration available at the receptor point. It can be calculated using following expression:

$$C_{ij} = \frac{1}{\sum_{l=1}^{M} m_{ijl}} \sum Clm_{ijl} \quad (1)$$

where C_{ij} corresponds to the average weighted concentration at the grid cell (i, j) while Cl is the measured mass concentration over Delhi. m_{ijl} is the number of trajectory end points with regard to Cl and m is the number of number of samples that have trajectory passing through the grid cell (i, j). Thus, the weighted concentration obtained from each grid signifies the expected mass concentration at the receptor point if the trajectories crosses through that specific grid. In this manner, we have calculated CWT for mean $PM_{2.5}$ mass concentration measured at Delhi. We also carried similar analysis using AOD at the receptor site. The results were similar and hence is not shown here.

The CWT analysis of $PM_{2.5}$ reveals the potential sources location or regions that lead to high loading conditions over Delhi during the post monsoon period. The CWT technique is capable to distinguish the major sources from the moderate one and can depict a clearer picture of spatial source pattern. The pathways of the major sources can also be found. Fig. 5 shows that states like Punjab, Haryana, which are located to the northwestern part of Delhi, are mostly responsible for the higher $PM_{2.5}$ concentrations over the city (mostly higher $PM_{2.5}$ levels than the NAAQS standard). It is interesting to note that CWT with high loading also corresponds to the regions with high concentration of fire detected by MODIS (blue dots in Fig. 5). This analysis shows that high-loading conditions over Delhi corresponds to trajectories traversing NW part of NCT and also those

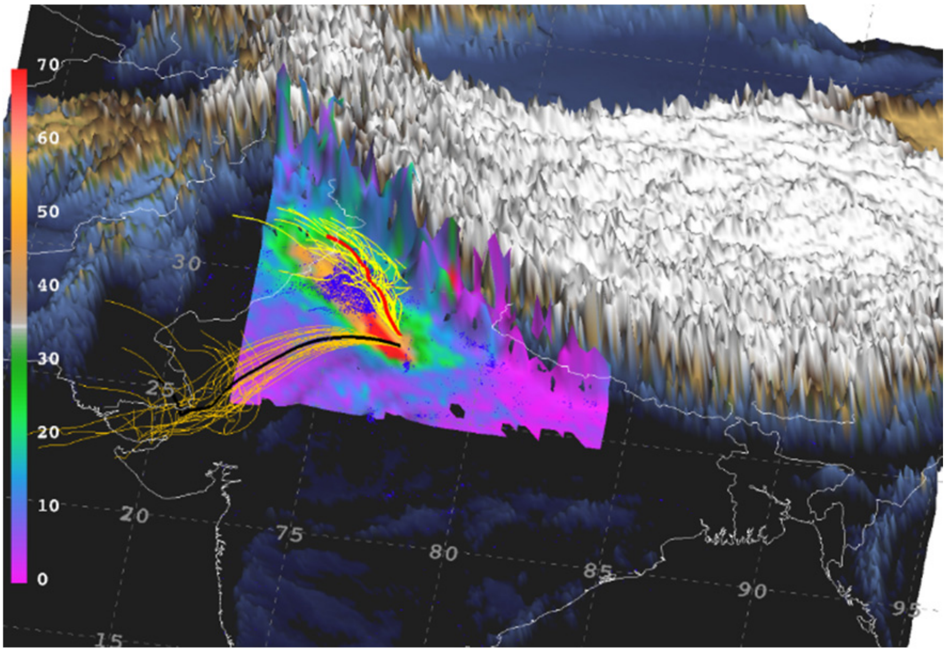

Fig. 5. Role of long-range transport on $PM_{2.5}$ concentration over Delhi. The color bar represents the expected $PM_{2.5}$ levels observed at Delhi using CWT. The black trajectory corresponds to the mean trajectory for low loading conditions, whereas the red trajectory corresponds to high loading condition. The blue dots represent biomass burning during 2016.

locations influenced by biomass burning. The crop residue burning is a normal practice during post-monsoonal months specially after harvesting (October and November). The burning of crop residue usually produces fine-mode anthropogenic aerosols, which are easily be transported by wind. From the figure, one can notice the surrounding areas of Delhi contributed less $PM_{2.5}$ with regard to the northwestern states. Thus during post-monsoonal months whenever there occurs a higher concentration of particulate matter over Delhi, highest amount of contribution is coming from northwestern region. The MODIS Terra Fire Counts detected over Punjab and Haryana during post-monsoon coincides with the high $PM_{2.5}$ loading CWT map. We also segregated the trajectories according to the higher and lower AOD values (two standard deviations with respect to the mean) during 2016. The yellow lines denote the high AOD trajectories while the golden lines represent low AOD trajectories. The red characterizes mean high AOD trajectory while black denotes the same for low AOD situation. From the figure, it is quite evident that high AOD trajectories always advect from northwestern part, which can bring fire-induced anthropogenic aerosols to the Delhi region while low AOD trajectories are longer in length and are coming from Arabian Sea or from southwest direction. Having found that NW part of NCT is a major source of aerosol loading during Diwali season; we explored how these fires are changing in the recent times.

Our analysis using 17 years of fire data reveals that the number of fire counts has been increasing by ~25% per year (Fig. 6). Combining CWT, fire count, trajectory analysis along with the variability in AOD, AAOD, UVAI, $PM_{2.5}$ both on climatological sense and during 2016, it may be concluded that one cannot neglect the effect of long-range transport from the surrounding states during higher pollution events over Delhi especially during post-monsoon season. This implies that both local and remote emission factors need to be considered to initiate air pollution control measures. As discussed earlier, the abnormally higher value of particulate matter and AOD along with peculiar long retention of heavy pollution level after Diwali 2016 can only be explained by the aspects of long-range transport of the pollutants. The high amount of particle and gases emitted during Diwali eventually enhanced the background concentration, which was further enhanced by the advected anthropogenic aerosols of biomass origin, which eventually caused the 2016 high pollution event. It appears that long-range transport or advection from remote sources are influential in modulating air pollution episodes over New Delhi.

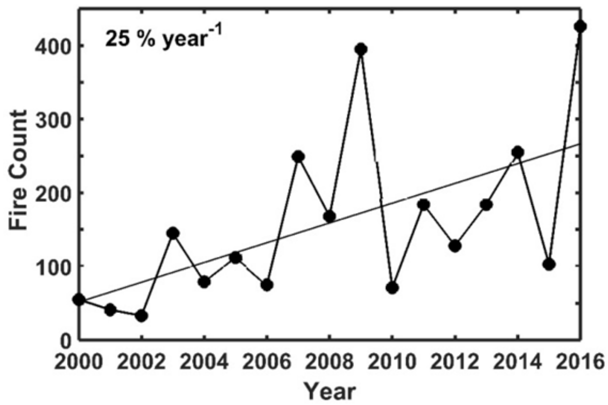

Fig. 6. Trend in Fire counts based on level3 (MOD14A1) fire products from MODIS (Terra) (2000–2016).

CONCLUSIONS

This analysis, which is based on 17 years of satellite measurements, along with $PM_{2.5}$ measurements since 2011, over Delhi, reveals the following:

1. Higher pollution levels are expected during and after Diwali.
2. The increased loading due to firecrackers and the associated emissions is normally expected to increase the $PM_{2.5}$ mass concentration by ~20–40% and the AOD by ~5%. However, long-range transport from other regions could either enhance or suppress these effects, depending on the origin and the route of an air mass.
3. The northwestern part of NCT exerts a large influence on the high loading conditions over Delhi.
4. HYSPLIT trajectory and CWT analyses in combination with the spatial pattern and density of detected fires (biomass burning) reveal that the 2016 severe air pollution episode/event during Diwali was caused by the advection of highly absorbing biomass burning aerosols from upwind regions (the NW quadrant).
5. Local pollution due to anthropogenic activities along with festivities may have only played a minor role during this episode.

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