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Research article

Numerical simulations of different sectoral contributions to post monsoon pollution over Delhi

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ABSTRACT

The National Capital Region (NCR) of India, Delhi, has experienced high post-monsoon pollution along with several peak pollution episodes in recent years. Diwali, the festival of lights, which is among the biggest festivals of India celebrated during the post-monsoon season, is also considered a pollution event associated as it is with the lighting of a large number of firecrackers. 2016 Diwali pollution episode continued for a week creating severe discomfort to residents of Delhi, prompting the judiciary to ban the sale and use of firecrackers in Delhi from 2017 onwards. The current study analyzes different sectoral and temporal emissions contribution to the 2016 post monsoonal pollution episode over Delhi using a fully coupled chemical transport model. The findings of the study indicate that aerosols produced from crop residue open burning at the northwestern states contributed more than 60% of the total simulated surface concentration during the period under study. Model experimental simulations show that despite emissions from within the city, what explains the severity of pollution over Delhi during the period under consideration is an additional pollution load emanating from these intense crop open burning sessions from nearby areas. Further, model simulations show that while Diwali emissions can elevate the pollution load over Delhi, the effects do not last beyond 48 h. It is found that the stagnation of the pollutants several days beyond the 2016 Diwali day was due to favorable meteorological conditions like low surface temperature, lower boundary layer height, and weak northwesterly winds. The study shows that in order to improve air quality in Delhi during the post-monsoon period, mitigation efforts should target the adjacent rural areas, especially when there is massive burning of crop residue in those areas.

1. Introduction

Global air pollution levels have altered significantly in the past two decades. The elevated concentration of the pollutants is such that they are able to alter the climatic system by altering the Earth's radiation budget (Fenger, 2009). Heavy air pollution can directly impact health and the livelihood of the population (e.g., Akimoto, 2003; Cohen et al., 2005; Gurjar et al., 2016; Pandey et al., 2017). Rapid socio-economic growth over South Asia has led to the increase of anthropogenic pollutants (e.g., $PM_{2.5}$ (particulate matters of size less than 2.5 μm), Black Carbon, Sulphate, Nitrogen Oxides (NO_x), surface ozone, etc.) over this region. The region is also impacted by biomass burning events (Venkataraman et al., 2006). The Indo Gangetic Plain (IGP) is one of the most populated areas of South Asia and the dense population coupled with industrial growth is leading to a high anthropogenic emission over this region (Bollasina et al., 2008; Ramanathan and Ramana, 2005; Tripathi et al., 2005). These elevated emissions, in turn, impact the air quality of the IGP, including megacities like Delhi.

New Delhi is considered as one of the most polluted cities in the world (World Health Organization, 2016). The elevated concentration of the atmospheric pollutants due to rapid anthropogenic activities now becoming a threat to the Delhi residents (Guttikunda and Goel, 2013; Maji et al., 2017; Pandey et al., 2005). Numerous studies have confirmed that the $PM_{2.5}$ concentration over Delhi remains high throughout the year and exceeds the National Ambient Air Quality Standards (NAAQS) most of the time (Mitra and Sharma, 2002; Sahu and Kota, 2017; Srivastava and Jain, 2007; Tiwari et al., 2013). According to Dholakia et al. (2013), r in the present emission control scenario, the critical air quality situation could continue even up to 2030. Taking into consideration the severity of the situation, the Delhi Government has temporarily imposed

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the odd-even rule whereby only ~50% of vehicles are allowed to operate on any given day. The scheme shows mixed results with some improvement during the winter period (Sharma et al., 2017).

Several studies have highlighted the significant high post monsoonal values of $PM_{2.5}$ over Delhi (Guttikunda and Calori, 2013; Guttikunda and Goel, 2013; Srivastava et al., 2011; Tiwari et al., 2013, 2012). A study by (Tiwari et al., 2014) found that the fraction of fine mode particulates is higher than coarse mode particles (~89%) during the post-monsoon season. It is not just surface concentration that is increasing as according to (Mukherjee et al., 2018), the post monsoonal aerosol optical depth (AOD) is also continuously increasing over Delhi with an annual rate of ~3.2% since 2001. Several researchers have also reported post monsoonal pollution episodes over Delhi, especially during Diwali (Mishra et al., 2015; Mukherjee et al., 2018; Sati and Mohan, 2014; Sawlani et al., 2018).

Known as the 'breadbasket' of India, Punjab and Haryana are located at the Northwestern end of Delhi (NCR). There are two crop-growing seasons for this area: summer (harvesting time between October and November) and winter (harvesting time between April and May) (Vadrevu et al., 2011). During the last 30 years, the tendency to use mechanized harvesters is increasing over this region. A recent study has found that more than 75% of the rice is harvested using the combine harvester (Vadrevu et al., 2011). However, the mechanized method also leaves a large amount of crop residue, which is burned by the farmers to prepare the field for the next cropping season (Kaskaoutis et al., 2014). This, in turn, creates large amounts of black carbon and other pollutants that slowly spreads throughout the IGP, including Delhi, with the help of weak northwesterly surface winds (Singh and Kaskaoutis, 2014). Using dual carbon isotope fingerprints, Bikkina et al. (2019) reported that rural biomass burning could contribute more than 42% of the post monsoonal Delhi pollution. Cusworth et al. (2018) has reported a significant rise in $PM_{2.5}$ concentration during each post monsoonal burning period from 2012 to 2016. The back trajectory analysis revealed that more than 80% of the northwesterly flow at the ground level intercepts the crop burning region before arriving in Delhi (Jethva et al., 2018).

Diwali or the festival of lights is one of the biggest festivals celebrated throughout India. Every year, during the festival, a large number of firecrackers are burnt, leading to the emission of numerous hazardous pollutants (sulfur dioxide, carbon dioxide, carbon monoxide, suspended particles, aluminum, manganese cadmium, etc.). Already several studies have been carried out throughout the country to evaluate the effect of Diwali emissions (Bhatnagar and Dadhich, 2015; Chatterjee et al., 2013; Chauhan et al., 2014; Ganguly, 2009; Nasir and Brahmaiah, 2015; Nigam et al., 2016; Ravindra et al., 2003). Most of these studies have reported a higher concentration of pollutants during the days of the Diwali festival. Several investigations in Delhi have attributed the post monsoonal rise of the pollutants to massive firecrackers burning during Diwali (Chauhan and Singh, 2017; Parkhi et al., 2016; Perrino et al., 2011).

However, these studies have not adequately estimated the influence of local Diwali emissions and open crop residue burning on the rise in particulate emission over Delhi in the post-monsoonal period. The current state of knowledge points to contribution from both local and transported pollutants to the high pollution episodes over the Delhi region. Hence, it is essential to distinguish between the contributions from local anthropogenic emissions, including Diwali time emissions, and the more regional open crop residue burning. The 2016 Diwali pollution episode is a particular event that provides insights into post-monsoonal pollution in Delhi. It was the high pollution loading during this period, which led the judiciary to ban firecrackers within the National Capital Territory region (NCR). The simultaneous occurrence of Diwali firecrackers burning and rural open biomass burning has provided us with a case study with which to examine the contributors to this pollution event. A recently published study using which applied carbon tracers concerning the 2016 Delhi episode has indicated that biomass burning was primarily responsible for the pollution spike (Sawlani et al., 2018). Another study using satellite observations combined with the concentration weighted trajectory (CWT) model also pointed towards biomass burning (Mukherjee et al., 2018). Though surface and columnar satellite observations provide an indication of the source region, they do not link concentrations with emission sources. Chemical transport models are more functional in that respect as they identify the source of the pollutants by altering the different emission inputs to the model. In this study, an attempt is made to identify the source of the pollutants responsible for the 2016 pollution episode and to quantify the different sectoral contributions to the post monsoonal pollution episodes over Delhi using a fully coupled online chemistry transport model.

2. Model setup and methodology

A chemical transport model has been utilized to distinguish the sectoral contribution of the pollutants over New Delhi. These models have several numerical and chemical equations that are simultaneously solved to predict the transport and source of different pollutants over a particular area defined by the user (called the model domain). In this study, the Weather Research and Forecasting model (Skamarock et al., 2008) version 3.8.1, coupled with chemistry (Fast et al., 2006; Grell et al., 2005) is used to generate the meteorology and pollutant concentration. The model domain ranges from 53° E to 99° E in the West-East direction covering 300 grid points and 7.6° N-35.6° N in the south-north directions (201 grid points) with a spatial resolution of 15×15 km^2. The vertical grid is composed of 30 vertical layers. The static geographical field is interpolated from the 10 min data generated by the United State Geological Survey (USGS) to the model domain using WRF preprocessing system (WPS). The National Center for Environmental Predictions (NCEP) Final Analysis (FNL) fields available at a spatial resolution of 1° x 1° are used for model initial and lateral boundary conditions. The detailed model description can be found in the additional information section.

To evaluate the model performance, the simulated meteorology is compared with the observational data. For this, the upper air radiosonde data from the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html) and surface meteorological data from NCDC (https://www.ncdc.noaa.gov/cdo-web/) are used. The validation is carried out using measurements from the Indira Gandhi International Airport (IGI), Delhi. The validation for the modeled surface air pollutants, the measurements from four Central Pollution Control Board (CPCB) stations (Shadipur, Dwarka, RK Puram, and Punjabi Bagh) were used. In addition, the satellite-derived level 2 Aerosol Optical Depth (AOD) with a horizontal resolution of 10 km is taken from MODIS Terra (MOD04_L2) in order to understand the post monsoonal variability in column loading of aerosols during the Diwali period. Mukherjee et al. (2018) showed that the $PM_{2.5}$ concentration was more than 100 μg/m^3 even before the 2016 Diwali day (30th October 2016). This concentration value had further increased to ~800 μg/m^3 by 5th November, which was 6–7 days after the Diwali event. Therefore considering Diwali day as the central day, model simulations were carried out for the entire period (in all, ten days before and after Diwali).

Four different simulations were carried out in order to separate the contribution from the local anthropogenic and distant open biomass burning (Table 1).

i) The first experiment (CTRL) contains all anthropogenic emissions (emissions due to human activity) along with emissions from biomass burning.
ii) In the second experiment, the fire emissions were turned off (CTRL-BB) to understand the effect of biomass burning on pollutant loading transported to New Delhi.
iii) The third experiment is designed to understand the contribution from the Delhi local emissions to the pollution episode. Thus all anthropogenic emissions within the boundary of Delhi NCR (76°-

Table 1. List of Simulations performed.

Case	Description
CTRL	All emissions including Anthropogenic and biomass burning
CTRL-BB	All emissions except biomass burning
CTRL-woD	No anthropogenic emissions from Delhi for the entire study period
CTRL + DD	Anthropogenic emissions were doubled for the Diwali day over Delhi

78° E and 28°-30° N) are turned off for the entire study period (CTRL-woD). The area includes 7 grid points, each from north-south and west-east directions, which cover 105 × 105 km^2 area.

iv) The final and the fourth experiment is designed to understand the impact of pollutants from New Delhi. The anthropogenic emissions were doubled (CTRL + DD) on Diwali day.

Studies have reported the pollutant concentrations on Diwali day are double or more than double that of its average concentration (Chauhan and Singh, 2017) and hence the last experiment.

3. Results and discussions

To understand the variability of post-monsoonal (September to November) $PM_{2.5}$ concentrations, six years (2011–2016) data available from CPCB sites in Delhi (Figure 1a) were analyzed. Here the individual station data was averaged and plotted. It shows high variability in post-monsoonal $PM_{2.5}$ with several high concentration days. It also shows that more than 50% of the days have concentrations higher than 100 μg/m^3. The post monsoonal average of $PM_{2.5}$ is ~184 μg/m^3, which is much higher than the NAAQS. The year 2016 is no different if we go by this comparison. Figure 1b shows that the variation of station (Shadipur, Dwarka, R K Puram, and Punjabi Bagh) averaged $PM_{2.5}$ over New Delhi during Diwali 2016. It shows a sharp rise in PM concentration on 5th -6th November, which is several days after the Diwali day (30th October). Hence, it is possible that elevated concentration is due to open burning. The images (Figure 2) show that there was constant biomass burning during the entire period of the study between 24th October and 5th November 2016.

3.1. Model performance evaluation

The variability of model generated meteorology, particularly temperature, relative humidity (RH), and wind speed (WS), were compared with observational data (Figure 3). Figure 3 a-c depicts the vertical variation of temperature, RH, and WS three days before the Diwali event, while Figure 3 d-f presents the three days after Diwali. The results show that the model is able to capture the vertical variation of the meteorological fields quite reasonably with an RMSE of ~0.8 °C and a correlation coefficient of ~0.99. While RH shows a significant dry bias at the surface level, upper level RH is predicted better. The observed vertical wind speed is simulated with a low RMSE of ~0.9 ms^{-1}. A previous study using WRF has also reported similar model performance over this region (Mohan and Bhati, 2011).

Figure 3 g-i shows the time series comparison between observed and modeled surface temperature, RH, and WS. It is seen that the magnitude of the temperature (RMSE ~1.4 °C) and wind speed (RMSE 0.9 ms^{-1}) is well simulated (see Table 2) with high and low biases. Our model simulations report agreement with surface observations better than previous studies such as those by Mohan and Bhati (2011). The model performance for RH is similar to a previous study by Marrapu et al. (2014) with an RMSE of 33.9 compared to our RMSE results of 32.05. This dry bias of RH can impact particle growth and the chemical characteristic of the particles, including the computation of aerosol optical depth. However, for this study, the focus is on trying to understand the accumulation of pollutants during a short time-frame in the post-monsoon season. Thus the RH bias was ignored for further analysis.

Overall, the model under-predicted the pollutant concentrations. The time series comparison between simulated and observed $PM_{2.5}$ (figure not shown) reveals that on certain days model values are 50% lower than that of the observed value. However, the model is well able to capture the pollutant temporal variation. Thus, the normalization method has been applied (divided by the maximum value) to compare the pollutant trends before and after the Diwali day (Figure 4). Four pollutants (CO, $PM_{2.5}$, SO_2, and Ozone) are compared with observational data over four CPCB station. As discussed earlier, the spike of $PM_{2.5}$ concentration appears on the 6th day from the Diwali day. Therefore a 6 days average concentration of the pollutants is computed before (and after) Diwali. Figure 4 gives the results. It shows that except for ozone, all the simulated pollutants match the observed trend. The post-Diwali observed concentrations are higher for both CO (Figure 4 a,e,i,m) and $PM_{2.5}$ (Figure 4 b,f,j,n), which the model also reproduces. SO_2 shows a decrease in concentration after Diwali for both observation and model simulations (Figure 4 c,g,k,o). Ozone formation is highly non-linear and occurs through complex reaction schemes (chemical and photochemical), which in the case of the Diwali event, is not captured by the model constructed for every emission scenario (Figure 4 d,h,l,p). Table 3 gives a statistical analysis of the model simulation with observations. The results show that the mean and standard deviation of the concentration values are within the range of each other.

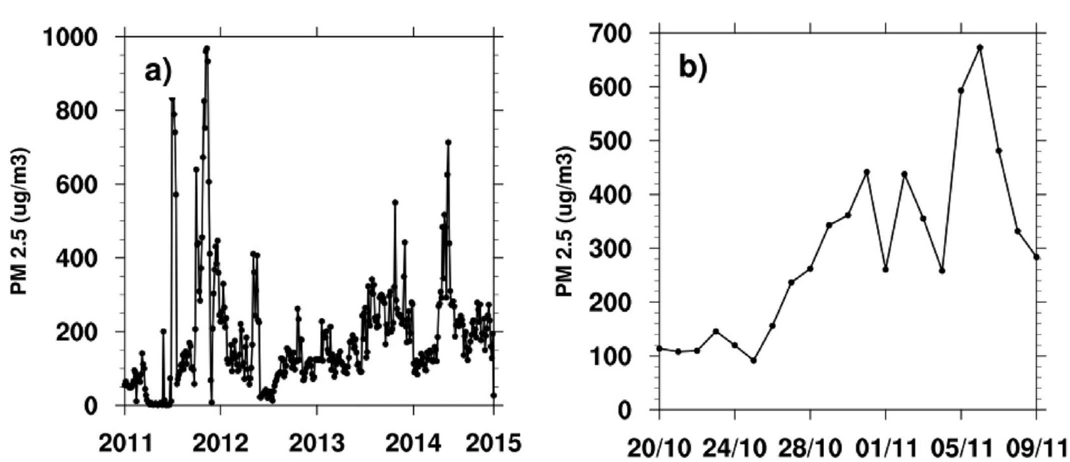

Figure 1. Variation of $PM_{2.5}$ over Delhi a) Post-monsoonal (September–November) $PM_{2.5}$ time series and b) 4 station-averaged time series of $PM_{2.5}$ during Diwali 2016

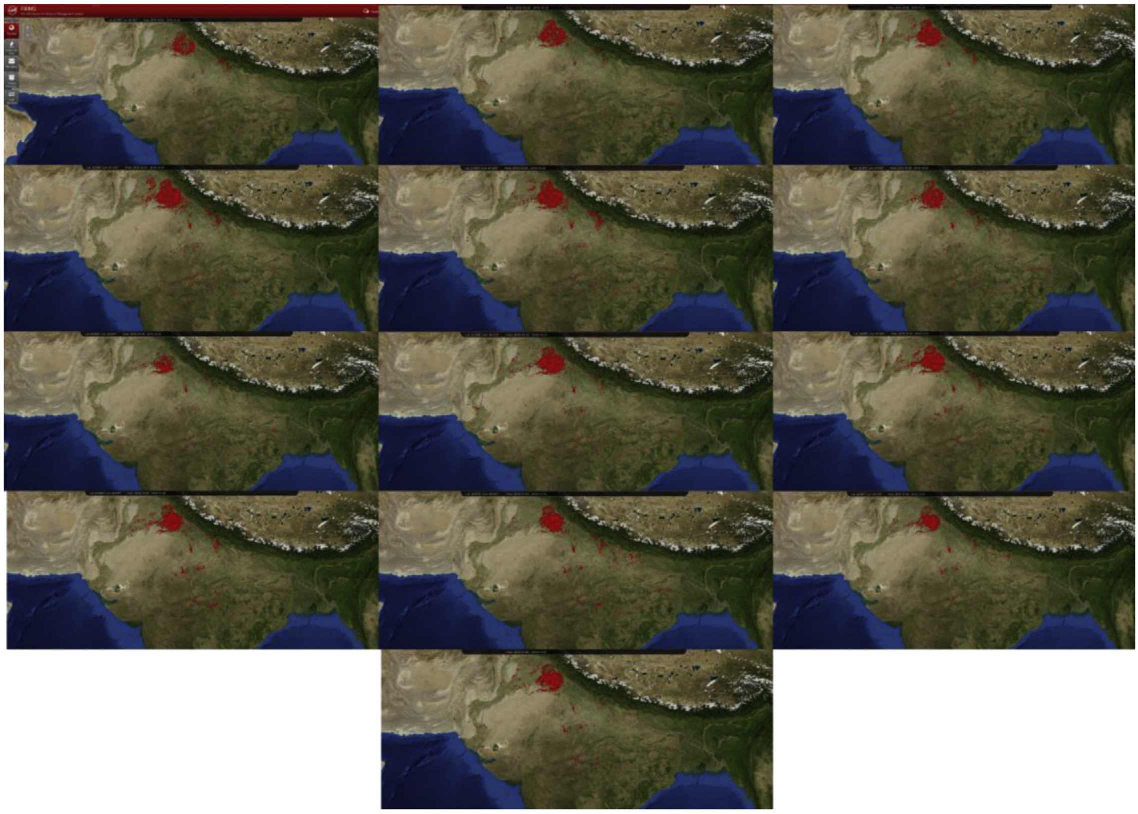

Figure 2. Fire points derived from MODIS Aqua from 6 days before to 6 days after Diwali (24/1016-05/11/16).

3.2. Case studies for 2016 diwali event

As discussed in the methodology section, the 2016 Diwali episode persisted for more than a week, and the pollutants reached the maximum concentration around the 5th of November 2016. Figure 5 shows the time series of model simulated pollutants (BC, $PM_{2.5}$, AOD, CO, SO_2, and ozone) during the 2016 Diwali period. Our control simulation (solid black line) is also indicating a sharp rise of pollutants on those particular days (Figure 5 BC, $PM_{2.5}$ and AOD plots). With the sharp rise in particulate matters like BC and $PM_{2.5}$ along with AOD and CO, it is evident that except for the CTRL-BB (dashed red line), all the runs (CTRL, CTRL-woD, and CTRL + DD) are able to produce the elevated pollutant level several days after the Diwali date. The experimental simulation without biomass burning (CTRL-BB), however, is not able to capture the increase in post-Diwali concentration and remains rather constant throughout the period.

BC and $PM_{2.5}$ concentrations decrease more than 60% in CTRL-BB compared to the control run. A recent study has also reported that aerosols generated from biomass burning during the post-monsoon season are responsible for ~42% of the pollution over Delhi (Bikkina et al., 2019). Even factoring in uncertainties in emissions of biomass burning, pollutant transport, and removal, our results are still similar to the observation based analysis.

The model further quantified the contribution of anthropogenic emissions to post-monsoonal pollutant loading in the NCR region by turning anthropogenic emission off from the entire NCR region keeping only emissions from elsewhere (simulation CTRL-woD). This would address some of the uncertainties related to the estimate of biomass burning emissions as there is more confidence in the anthropogenic emissions (Zhao et al., 2011). The results show that even without having any emission from the NCR for the entire study period (CTRL-woD), there is still pollutant accumulation in post-Diwali time, and the concentration values differ by ~10% for concentrations calculated by the control run for $PM_{2.5}$ and BC. This implies that the local sources made only a minor contribution to the 2016 episode. It also gives an insight into how megacities like Delhi could experience pollution episodes based solely on transported aerosols from the surroundings. There is more written on megacity contribution to regional air pollution (e.g., Guttikunda et al., 2003), whereas this study has reported a case where the surrounding rural region is contributing more to megacity pollution. The findings are compatible with reports from observation-based analyses as well (Jethva et al., 2018; Mukherjee et al., 2018).

To further understand the impact of Diwali emission, another experiment was designed. To account for Diwali emissions, which are not incorporated in the model simulations of CTRL, CTRL-BB, and CTRL-woD, all the anthropogenic emissions were doubled for the Diwali day. As mentioned before, Chauhan and Singh (2017) and others have reported a doubling or more than doubling of pollutant concentration during Diwali day. So assuming linear relationships for at least the primary pollutant, the emissions were doubled for all species. The results provided in Figure 5 (green line) shows that while the concentration does increase significantly for some of the pollutants on the day of Diwali, the elevated concentration is quickly diffused throughout and the model does not show any increase in pollutant concentration in the particular mode grid beyond 48 h. This result further affirms that while instantaneous emissions do contribute to elevated pollutant loading over the region, the concentrations quickly return to the original level if the emissions are not sustained for a significant period. Data of Figures 1, 3, and 5 can be found in the Supplementary Material.

To further verify the analysis, the percentage change of the pollutants before and after Diwali (Figure 6) is investigated with respect to the value observed during the Diwali day. Figure 6 shows the pollutant percentage change for three different time periods (3 days, 6 days, and 10 days) (see Table 4 for values). Even in the CTRL + DD run, the 10-day average is much higher than the 3-day average. This further indicates that the Diwali day emissions have a smaller contribution than regional emissions to the pollution load during this pollution episode. However, the CTRL-BB run shows very little change in percentage, signifying that the temporal average is primarily governed by biomass burning. Since

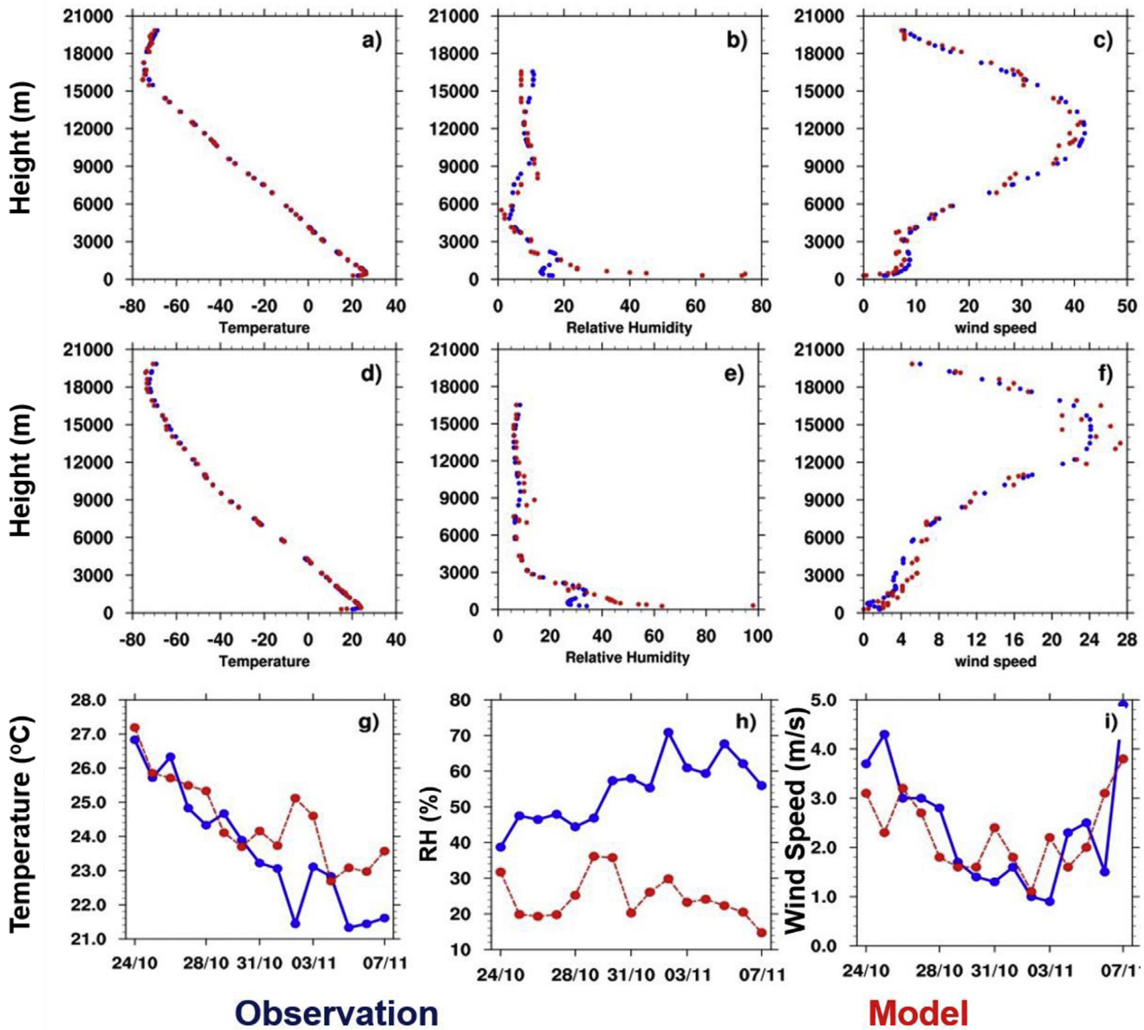

Figure 3. Evaluation of the meteorological performance of the model. Vertical variation and time series of Temperature (a,d,g), Relative Humidity (b,e,h), and Wind Speed (c,f, i) three days before and after Diwali.

meteorology for all these runs is similar except for changes due to meteorology in the model, the concentration difference between these model runs is mostly driven by emissions. At the end of this section, the impact of biomass burning aerosol on meteorology during this period is discussed.

Finally, in order to identify the source region of the pollutant, the spatial variation in BC concentration before and after Diwali is examined (Figure 7). The figure shows the 6 and 3 day's average of BC before and after Diwali along with the modeled Diwali day concentration. The black dot represents the location of Delhi on the map. The figure shows that except for CTRL-BB, all the three runs show a swath of high BC from the northwestern part of Delhi. This suggests that BC originating from biomass burning over this region increases the pollutant concentration over Delhi. A continuous high fire count over this region during this period (see Figure 2) supports our observation. Thus it can be concluded that the aerosols originating from crop or biomass burning over the northwestern part of Delhi (mostly Punjab and Haryana) are primarily responsible for the 2016 pollution episode. The impact of local anthropogenic emissions or the Diwali event is minimal as compared to biomass burning.

Table 2. Comparison of predicted meteorological parameters with observations.

	Temperature (°C)	Relative Humidity (%)	Wind Speed (ms^{-1})
Mean-Obs	23.64	54.63	2.39
Mean-Model	24.49	24.59	2.29
RMSE	1.38	32.05	0.93

The above discussion shows that biomass burning has played a significant role in elevating the pollutant concentration. However, stagnation or dispersion of pollutants largely depends on the meteorological conditions of the region. Therefore, the changes in meteorological parameters due to biomass burning are investigated. Figure 8a shows that surface temperature was continuously decreasing throughout the study period. During 4th November, the simulated temperature reaches its minimum value. The observational studies of the 2016 Diwali episode also reported the same reduction date (Sawlani et al., 2018). The model simulation shows that the temperature is only slightly modified by the inclusion of biomass burning (0.01–0.66 K). Black carbon is one of the major pollutants emitted during open crop burning. Multi model studies in various parts of the world have shown that high BC concentration can

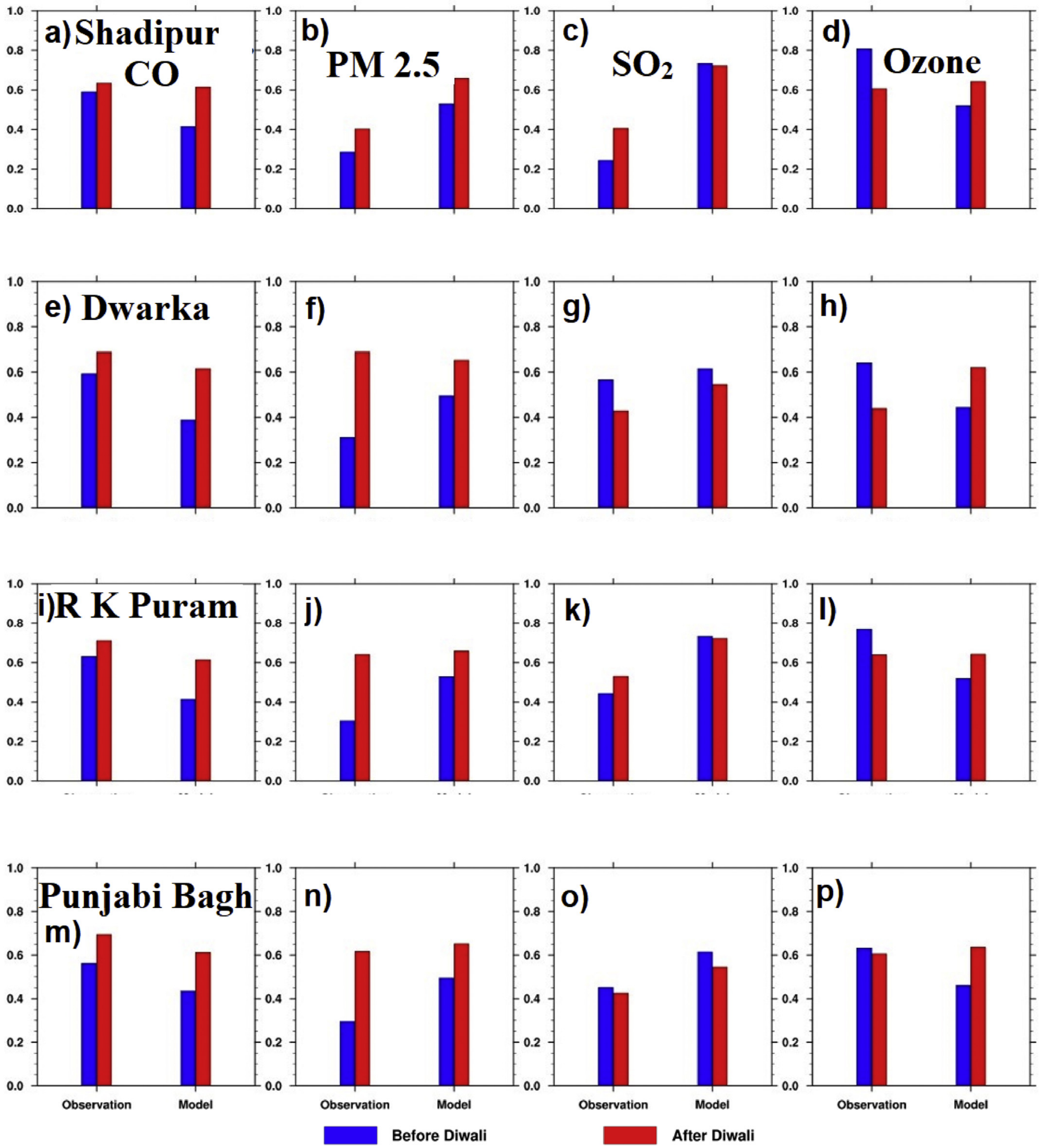

Figure 4. Normalized pollutant comparison between observed and model data over four CPCB stations before and after Diwali. Figure a,e,i,m represent the CO comparison over four stations. Figure b,f,j,n represent $PM_{2.5}$ comparison while c,g,k,o represent SO_2 and d,h,l,p represents Ozone comparison.

Table 3. Comparison between observed and simulated pollutants.

		RMSE	Correlation	Average (Observation)	Average (Model)	Standard Deviation (Observation)	Standard Deviation (Model)
Shadipur	CO	629.09	0.54	1748.00	1466.75	547.60	556.75
	SO_2	47.44	-0.23	10.39	54.51	7.10	13.03
	O_3	17.48	0.00	12.16	24.48	3.93	10.29
	$PM_{2.5}$	226.99	0.13	270.25	141.52	203.04	38.88
Dwarka	CO	1254.92	-0.27	801.93	1721.27	318.66	703.54
	SO_2	23.49	-0.48	11.92	30.78	4.33	11.00
	O_3	25.38	-0.37	19.66	32.53	8.57	15.58
	$PM_{2.5}$	204.76	-0.06	285.79	141.14	145.18	43.32
RK Puram	CO	2385.49	-0.06	3754.44	1392.78	534.87	491.95
	SO_2	31.95	-0.46	27.80	54.51	8.98	13.03
	O_3	12.57	-0.22	26.05	24.48	5.13	10.29
	$PM_{2.5}$	274.29	-0.04	361.46	142.54	177.53	40.14
Punjabi Bagh	CO	2331.03	0.39	3675.94	1412.87	1036.15	476.61
	SO_2	16.98	0.11	22.54	30.78	9.56	11.00
	O_3	16.99	0.26	31.87	29.57	10.73	11.55
	$PM_{2.5}$	315.67	0.24	391.66	141.14	203.43	43.32

reduce the surface temperature by 1–2 K (Liu et al., 2018; Samset et al., 2016).

The study also examined the changes in planetary boundary layer height (PBLH) due to the inclusion of open crop residue burning as this parameter also influences modeled pollutant concentration. The PBLH also showed a sharp decrease on 4th November (Figure 8b). The figure shows that the PBLH was largely impacted by the biomass burning (by as much as 7–298 m). Several researchers had previously reported that the boundary layer could be suppressed by elevated black carbon concentration (Gao et al., 2018). The study reported that a large amount of BC increases the heating rate by absorbing more shortwave radiation, which in turn increases the upper boundary layer temperature. This eventually leads to the formation of a temperature inversion at the surface level, which suppresses the PBL height. In that study, the PBLH height changed more than 400 m.

Another important meteorological variable that modulates the observed concentration is wind speed. Figure 8c shows that the wind speed also remains low during the period under study when biomass burning was included in the simulation, although the magnitude was not very high (with changes only up to 0.67 m/s).

Thus lower surface temperature, low PBLH, and low wind speed provided favorable conditions for the pollutant stagnation during the 4th and 5th of November, which eventually further increased the pollutant concentration. The rise of the PBL height, along with wind speed after the

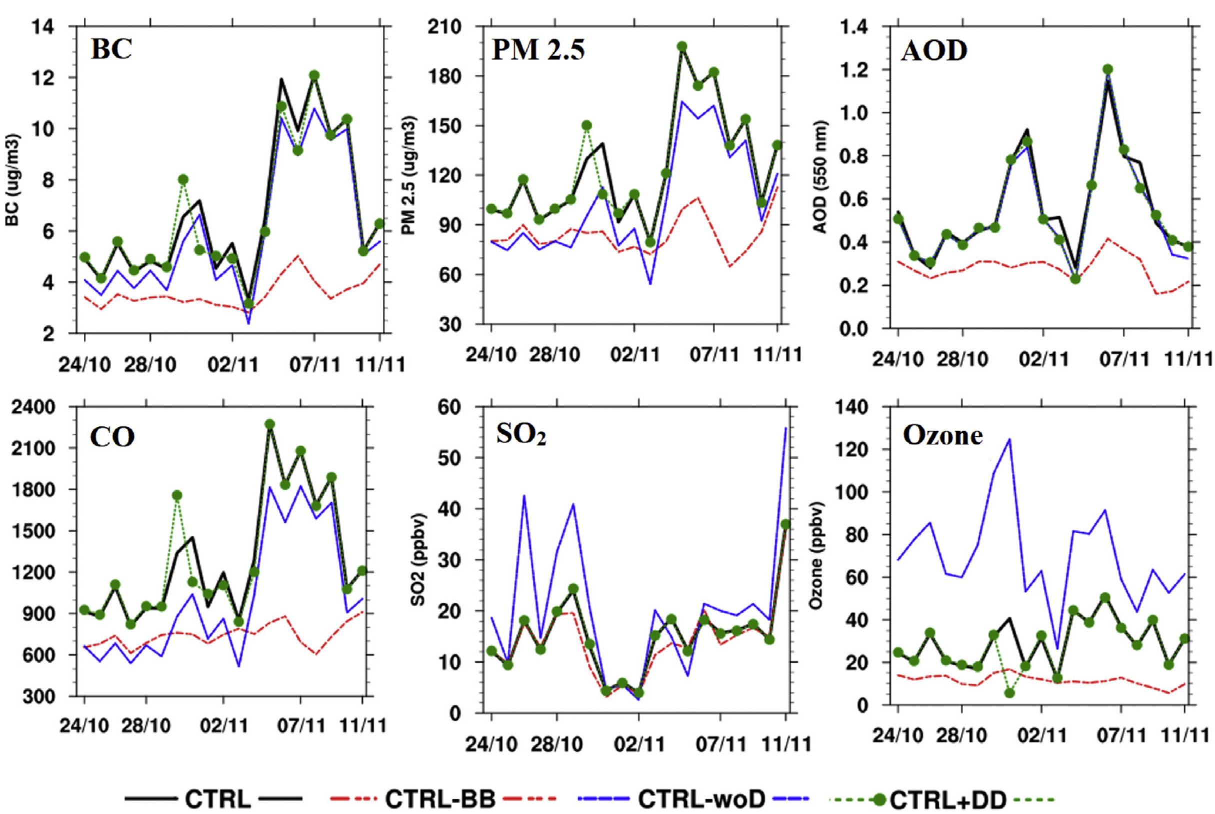

Figure 5. Time series of the pollutants during 2016 Diwali period (24/10/2016-07/11/2016).

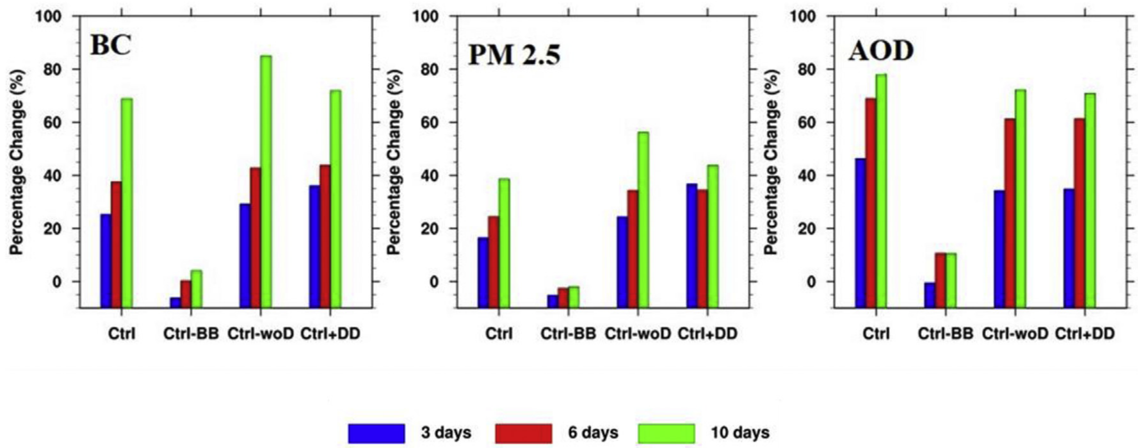

Figure 6. Percentage change in the average BC, $PM_{2.5}$, and AOD before and after Diwali for 3, 6 and 10 days.

Table 4. BC percentage change for three different periods.

	3 Days	6 Days	10 Days
Ctrl	16.55	24.53	38.67
Ctrl - BB	-5.14	-2.45	-1.93
Ctrl - woD	24.44	34.36	56.23
Ctrl + DD	36.80	34.49	43.82

6th of November, dispersed the pollutants from this grid location. The model simulations thus show a positive feedback system during the intense biomass burning period with the rise in pollution impacting meteorology, which further creates favorable conditions for an increase in concentration.

3.3. Features of other diwali periods

From the above discussion, it becomes evident that the contribution from the Diwali firecrackers to post monsoonal Delhi pollution is less than the biomass burning aerosol. However, one could argue that this is only the scenario of 2016. Therefore, the variability of AOD (MOD04_L2) during several other Diwali periods are examined (Figure 9). The figure shows that the highest AOD values occur either before or after Diwali. If the increase in pollutants directly depends on the Diwali emissions, an immediate rise in AOD should occur after the Diwali day. Thus, it can be concluded that biomass burning, rather than Diwali emissions, has more impact on the post-monsoonal pollutant spike over Delhi. The data for each line plots can be found in the supplementary material.

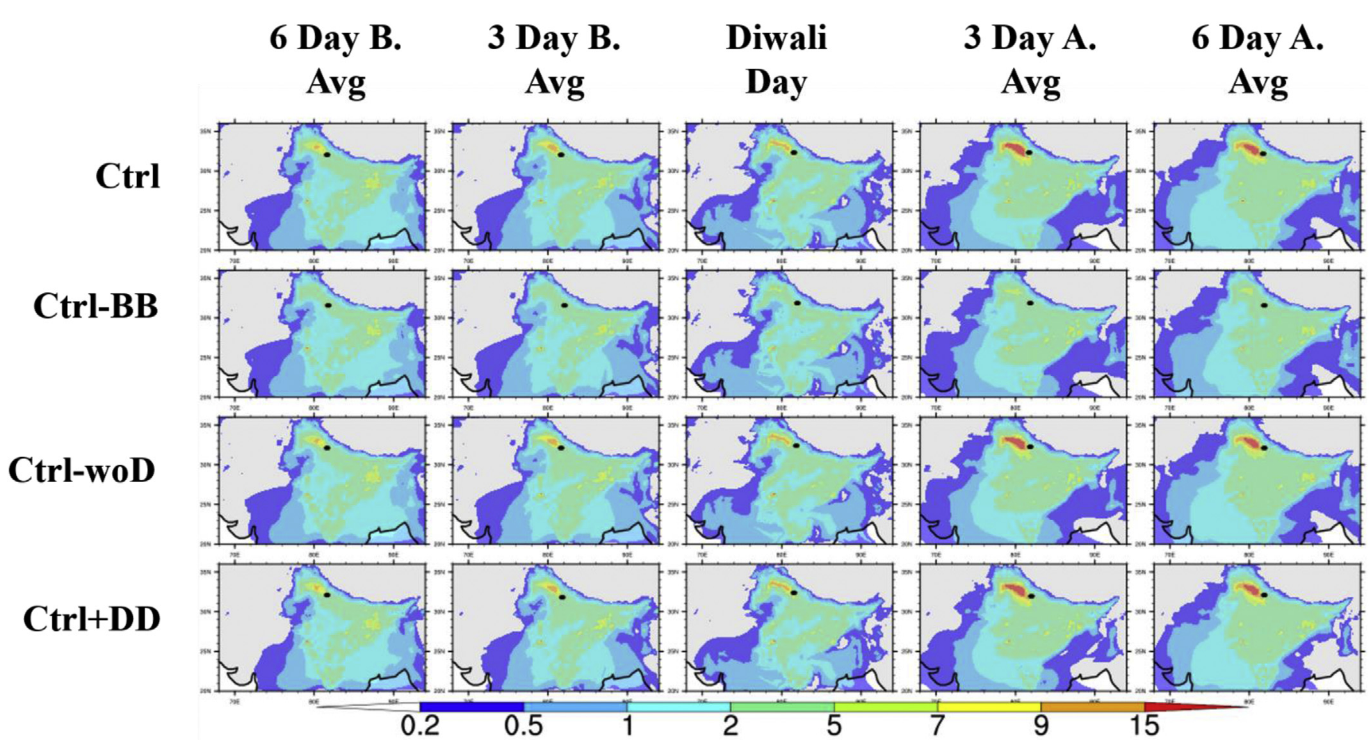

Figure 7. Spatial variation of BC concentration before and after Diwali.

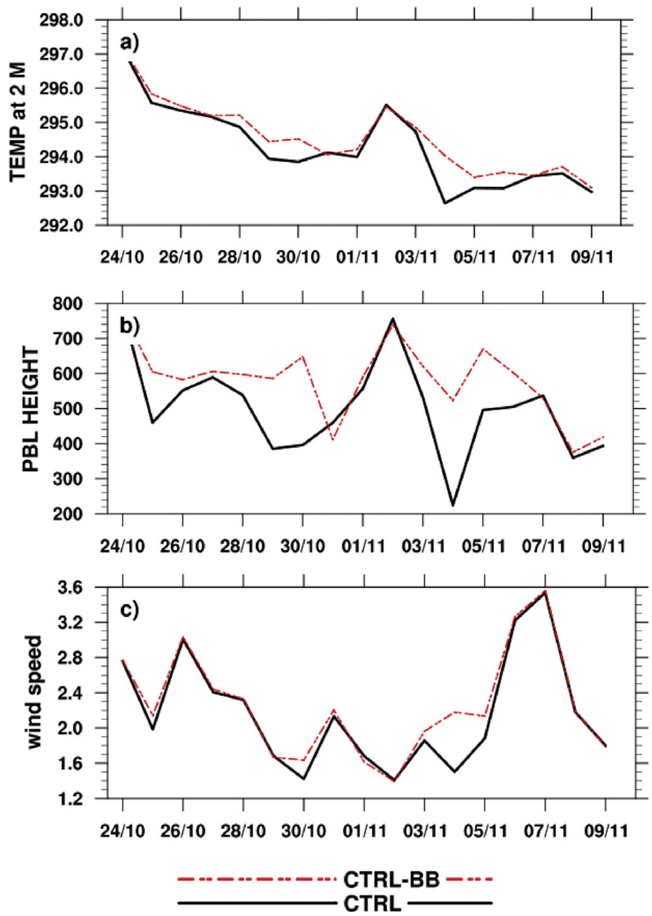

Figure 8. Time series of the a) 2 m air temperature b) PBL height and c) 10 m wind speed over Delhi.

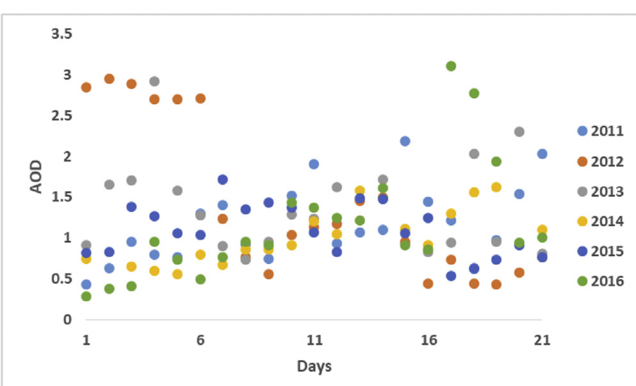

Figure 9. Variation of AOD over Delhi before and after Diwali period (2011–2016).

4. Conclusion

The present study has revealed the sectoral contribution to the post-monsoon pollution over Delhi. The Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) was used to understand the sectoral and temporal contribution of different emissions to air quality over Delhi. The climatological analysis of pollutants in and around Diwali day reports maximum values for either before or after the actual Diwali day. The model based simulation suggests that while extra emissions arising from Diwali-related activities do increase the pollutant concentration, the impact of this emission does not last beyond 48 h. Instead, much of the elevated post-monsoon contribution in the model simulation is seen to originate from biomass burning from Punjab and Haryana region. The exclusion of the severe biomass (crop) burning over Punjab, Haryana, cannot generate high values of the pollutants observed, which implies the importance of crop burning for the rise of the pollutants over Delhi.

The model results show that it does not lead to a significant decrease in pollutant concentration, even if anthropogenic emissions were to be turned off. Results thus provide insight into why an experimental design such as odd/even transport experiments in Delhi may not be the solution to pollution during these particular periods.

The minimal contributions from Diwali day emissions confirm that emissions from the firecracker burning during Diwali are not solely responsible for the 2016 pollution episode. Instead, as shown above, the favorable meteorological conditions also support pollutant accumulation. The study thus provides insight into a less common instance where regional air pollution significantly affects megacity pollution as opposed to the more common instance where megacity emissions pollute the surrounding region.

Declarations

Author contribution statement

T. Mukherjee, B. Adhikary: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

V. Vinoj: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

S. K. Midya, S.P. Puppala: Conceived and designed the experiments; Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

For a particular simulation, the user needs to specify the different model physics needed. Two moment cloud microphysics scheme (Morrison et al., 2009) is applied to the model for cloud physics. The Rapid Radiative Transfer Model for General circulation models (RRTMG) (Iacono et al., 2008) is applied for the short- and long-wave radiative transfer in the atmosphere, which allows the online interaction between aerosols and meteorology. The Unified Noah Land Surface Model (Tewari et al., 2004) and revised MM5 scheme (Jiménez et al., 2012) represent the surface process in the model. The boundary layer processes are parameterized using Mellor–Yamada Nakanishi Niino (MYNN) Level 2.5 scheme (Nakanishi and Niino, 2009).

Along with Model physics, the model also requires background chemical concentrations, anthropogenic emissions, biogenic emissions, and fire emissions for a successful simulation. Ozone and Related Chemical Tracers (MOZART-4) chemical scheme (Emmons et al., 2010) is utilized to represent the gas-phase chemistry along with Goddard Chemistry Aerosol Radiation and Transport (GOCART) bulk aerosol scheme (Chin et al., 2002; Pfister et al., 2011) to represent the aerosol processes. MOZART-4 (Emmons et al., 2010) supplies the initial and lateral boundary conditions for the chemical species. The anthropogenic emissions of different species like CO, NO_x, SO_2, NH_3, CH_4, PM_{10}, $PM_{2.5}$, BC, OC and Non-methane volatile Organic Compound (NMVOC) is taken from the Emission Database for Global Atmospheric Research (EDGAR) HTAP global emission inventory (Janssens-Maenhout et al., 2012). The daily varying species originates from biomass burning are taken from NCAR Fire Inventory (FINN v1.5) data (Wiedinmyer et al., 2011). Additionally, the online plume rise model (Freitas et al., 2007) is applied to calculate the vertical distribution of the hot gases and particles emitted from biomass burning. The model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.04 (Guenther et al., 2006) is used to calculate the biogenic emission of the trace species from the terrestrial atmosphere.

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