



## Research article

## Impact of crop residue burning in Haryana on the air quality of Delhi, India

Pallavi Saxena<sup>a,\*</sup>, Saurabh Sonwani<sup>b</sup>, Ananya Srivastava<sup>c</sup>, Madhavi Jain<sup>d</sup>, Anju Srivastava<sup>e</sup>, Akash Bharti<sup>f</sup>, Deepali Rangra<sup>g</sup>, Nancy Mongia<sup>g</sup>, Shweta Tejan<sup>e</sup>, Shreshtha Bhardwaj<sup>g</sup><sup>a</sup> Department of Environmental Sciences, Hindu College, University of Delhi, Delhi, India<sup>b</sup> Department of Environmental Studies, Zakir Husain Delhi College, University of Delhi, New Delhi, India<sup>c</sup> Department of Economics, Hindu College, University of Delhi, Delhi, India<sup>d</sup> School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India<sup>e</sup> Department of Chemistry, Hindu College, University of Delhi, Delhi, India<sup>f</sup> Department of Mathematics, Hindu College, University of Delhi, Delhi, India<sup>g</sup> Department of Physical Science Chemistry, Hindu College, University of Delhi, Delhi, India

## ARTICLE INFO

## Keywords:

Biomass burning  
Air mass movement  
Rabi  
Kharif  
Meteorology

## ABSTRACT

Crop residue burning (CRB) over northern India is a major air quality and human health issue. The present study assesses the impact of PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub>, emitted during CRB activities in Haryana on the air quality of Delhi. The transition from pre-burning to burning period, in both rabi and kharif seasons, shows considerable increase in pollutant concentrations. PM<sub>10</sub> and PM<sub>2.5</sub> concentrations exceeded NAAQS limits by 2–3 times, while NO<sub>2</sub> and SO<sub>2</sub> stayed within the limits. MODIS fire observations used to estimate CRB fire counts (confidence ≥80%) shows that rabi (burning period) fires in Haryana are ~3 times higher and more intense than in kharif. Furthermore, backward trajectories shows air mass movement from Haryana, Punjab and Pakistan. Thus, pollutants emitted reach Delhi via air masses, deteriorating its air quality.

Meteorological conditions influence pollutant concentrations during both seasons. Frequent dust storms in rabi, and Dusshera and Diwali firework celebrations in kharif season exacerbate air pollution. In rabi, PM<sub>10</sub> and PM<sub>2.5</sub> have a significant negative association with (relative humidity) RH and positive association with (air temperature) AT. High AT during pre-monsoon, accompanied by low RH, loosens up soil particles and they can easily disperse. Stronger winds in rabi season promote NO<sub>2</sub> and SO<sub>2</sub> dispersion. In kharif, lower AT, higher RH and slower winds exist. Both PM<sub>10</sub> and PM<sub>2.5</sub> have a negative association with AT and (wind speed) WS. With lower temperature and slower winds during winter, pollutants are trapped within the boundary layer and are unable to disperse. As expected, NO<sub>2</sub> has a significant negative association with AT in Haryana. However, in case of Delhi, the association is significant but positive, and could be due to the odd-even scheme imposed by the Delhi government. More research is needed to determine the health effects of Haryana's rabi CRB activities on Delhi.

## 1. Introduction

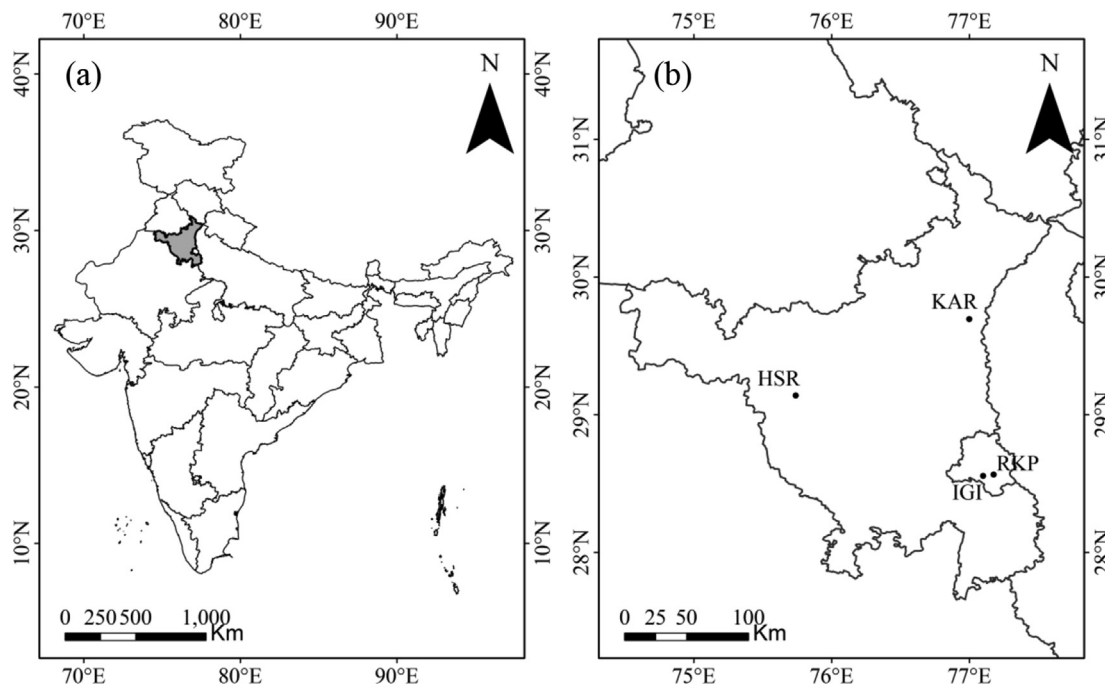
Biomass burning is an important source of atmospheric particulate matter (PM) and trace gases, which has a significant impact on local and global climate, in addition to causing severe health risks for humans (Zhang et al., 2011; Wang et al., 2013). Biomass burning includes various types of forest fires and agricultural burning after crop harvest, typically known as crop residue burning (CRB) (Singh et al., 2010; Rana et al., 2019). At a global scale, as much as 90% of wildfires are attributed to CRB and forest removal activities, are mostly restricted to Amazonia, Africa and Asia (Prabhu et al., 2020). The remaining 10% is largely due

to fires in wild forests and grasslands (Rana et al., 2019). Moreover, biomass burning, particularly, during and after crop harvest, emits massive quantities of gaseous and particulate pollutants, which often increases pollution at local and regional scales (Crutzen and Andreae, 1990; Langmann et al., 2009; Wang et al., 2013; Tsay et al., 2016; Jethva et al., 2019). The severity of pollution is greatly dependant on the amount of biomass burnt, air mass transport, wind direction and the distance from CRB source (Witham and Manning, 2007; Targino et al., 2013).

In developing countries, quickly clearing arable lands via CRB is a general practice adopted by farmers to directly increase the yield. In Asia,

\* Corresponding author.

E-mail addresses: [pallavisaxena@hinducollege.ac.in](mailto:pallavisaxena@hinducollege.ac.in), [pallavienvironment@gmail.com](mailto:pallavienvironment@gmail.com) (P. Saxena).



**Figure 1.** Geographical location of (a) the states of Haryana and Delhi (shaded) within the Indian boundary and (b) selected study sites within Haryana, viz. Hisar (HSR) and Karnal (KAR), as well as Delhi, viz. Ramakrishna Puram (RKP) and Indira Gandhi International (IGI) Airport.

forest fires (45%), CRB (34%) and grassland fires (20%) contribute the most in terms of burning activities (Mittal et al., 2009; Tang et al., 2013). Furthermore, CRB generates a large number of air pollutants such as oxides of nitrogen ( $\text{NO}_x$ ), sulphur dioxide ( $\text{SO}_2$ ), carbon monoxide (CO), volatile organic compounds (VOCs) and PM, which alters the air quality and affects various atmospheric feedback processes (Badarinath et al., 2009a, 2009b; Alexaki et al., 2019). Several other studies report increased concentrations of tropospheric ozone ( $\text{O}_3$ ), CO and aerosols due to CRB over various parts of Central Africa, South America and some parts of Asia due to long-range transport effect (Arola et al., 2007; Dumka et al., 2019). Besides, the direct adverse short and long-term impacts on the environment, poor air quality due to CRB presents a serious risk to human health. A recent study estimated that people residing in Punjab, an agriculturally dominant state of India, spent over USD 1 million annually to cover for CRB-related pollution exposure illnesses (Alexaki et al., 2019).

India is one of the largest agro-based economies in the world, producing the highest rice and wheat yield. As such, crop cultivation and harvesting-related activities are conducted throughout the year. The ever increasing production of agro based products consequently generates more waste and environmental pollution (Chang and Song, 2010; Dumka et al., 2019). However, a rapidly growing demand for food translates into a constant ramping up of yield production, which increasingly forces farmers to burn fields after harvest. India is ranked as the second-highest CRB contributor (84 Tg/year) in the world (Grover and Chaudhry, 2019). Additionally, in India (as well as Haryana), rice and wheat are sown during June–July and November–December respectively, and then harvested in the coming months of October–November and April–May, respectively (Gadde et al., 2009). In practice, this leaves farmers with a short time window, typically 3–4 weeks, to switch to the next season. Moreover, there are no economical technologies available for small fields that can collect leftover agricultural residues (Cheng et al., 2014; He et al., 2015). Therefore, the farmers prefer in-situ CRB, a practice that is less time-consuming, inexpensive and quickly prepares the field for the next crop (Venkataraman et al., 2006).

The total amount of agricultural waste generated annually in India is much greater than that in other countries. According to the Ministry of New and Renewable Energy (MNRE) estimates, an average of 500 Mt of

crop residue is generated in India each year, a majority portion of which is used as fuel for industrial and domestic purposes (Bhuvaneshwari et al., 2019). Concurrently, Streets et al. (2003) identify Punjab (~20 Mt), Haryana (~10 Mt) and Uttar Pradesh (~11 Mt) as the Indian states with the largest crop burning volume. These states form a part of the Indo-Gangetic Plains (IGP), over which the air quality in recent years has severely deteriorated due to CRB (Badarinath et al., 2006; Jain et al., 2014; Kaskaoutis et al., 2014; Jethva et al., 2018, 2019). In 2016, an overlapping episode of seasonal CRB and the wide-scale firecracker burning during Diwali resulted in poor air quality over Delhi and its adjoining areas (Chauhan and Singh, 2017). The study also highlights that, as a consequence, haze and smog prevailed during most days of October. In addition, Kaskaoutis et al. (2014) estimate that paddy residue generated in India is ~97 Tg/year, of which ~24% is commonly burnt in fields as surplus. However, Punjab and Haryana alone contribute about half of the paddy straw surplus generated per year (Gadde et al., 2009). Lohan et al. (2018) note that in Haryana, rabi CRB residue was nearly thrice as compared to kharif CRB. Additionally, Yadav et al. (2014) report that rabi CRB area in Haryana was also higher as compared to kharif CRB area. Besides Haryana, Punjab is one of the most widely studied contributor of CRB in northern India.

Interestingly, some studies have shown that rabi CRB is higher than kharif CRB (Yadav et al., 2014; Grover and Chaudhry, 2019). Unlike Punjab, in Haryana rabi CRB poses a much serious issue than kharif CRB (Lohan et al., 2018). Moreover, low soil moisture and high air temperature also contribute to increased fires and enormous loss of crops during rabi harvesting. Farmers in Haryana also reported that machinery sparks generated during threshing, are also responsible for biomass fires (Jitendra et al., 2017). Scientific research on the degradation of air quality over Delhi due to prevalent CRB activities in the neighbouring state of Haryana, particularly in rabi season, is still quite sparse. Most previous studies have focussed on the issue of CRB activities in Punjab, particularly in kharif season, in degrading the air quality of northern India. But these studies fail to discuss the role of rabi CRB in Haryana on degrading the air quality of Delhi. Delhi is of focus due to the fact that it is the national capital of India, has a population of over 16 million (2011 census), and remains one of the most polluted cities in the world.

Therefore, the present study seeks to (1) quantify CRB activities through fire count analysis in Haryana, (2) identify air mass movements through backward trajectories to Delhi from source locations, and (3) assess the variations in PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> concentrations, during pre-burning and burning periods of rabi and kharif season, in Haryana and Delhi. Overall, this study highlights the role of Haryana's CRB activities, particularly during rabi season, in deteriorating the air quality of Delhi.

## 2. Study area

### 2.1. Delhi

Apart from being India's national capital, Delhi is the second most populous city in the world (Mahato et al., 2020). According to the latest census report, the metropolis had a population of 16.8 million with an annual growth rate of 21%. It occupies an area of 1483 km<sup>2</sup>, and is located at an elevation of 220 m.a.s.l. (Saxena et al., 2020a, b). Delhi experiences a semi-arid climate with four main seasons: pre-monsoon (Mar–May), monsoon (Jun–Sept), post-monsoon (Oct–Nov) and winter (Dec–Feb). The temperature varies between 4 °C and 10 °C during winter and 42 °C and 48 °C during pre-monsoon (Saxena et al., 2019). Over 80% of yearly rainfall occurs during monsoon (Perrino et al., 2011; Tiwari et al., 2013; Sonwani and Kulshrestha, 2019). Two representative sites of Delhi were chosen for the study to recognise the impact of CRB from Haryana. The locations of these sites are shown in Figure 1.

#### 2.1.1. Ramakrishna Puram (RKP)

RKP (latitude: 28.56° N; longitude: 77.17° E) is one of the largest housing colonies in Delhi. It is surrounded by around 10 schools and 7 adjoining marketplaces. It is covered by the ring road to the north, outer ring road to the south with moderate traffic density.

#### 2.1.2. Indira Gandhi International (IGI) airport

IGI Airport (latitude: 28.55° N, longitude: 77.10° E) is one of the largest and busiest sites in Delhi. It is situated at a distance of 3 km from the national highway (NH 8) in the southeast and Gurugram in the southwest. This site is a very heavy traffic zone, where low floor buses, taxis, personal cars, three-wheelers and heavy duty trucks are common. There are no industries in the vicinity of the airport.

### 2.2. Haryana

Haryana is a state in northern India located at 29.05° N, 76.08° E and approximately 210–275 m.a.s.l. The state has an administrative area of 44,000 km<sup>2</sup>. The population is about 25.4 million (Grover and Chaudhry, 2019). The temperature ranges from 45 °C to 47 °C in pre-monsoon and 2 °C to 5 °C in winter. Like Delhi, Haryana also experiences ~80% of its rain during June–August. Haryana is also one of the major producers of rice and wheat in the country (Grover and Chaudhry, 2019). Two representative sites of Haryana were chosen, namely Hisar and Karnal (Figure 1), as they are one of the main wheat/rice CRB regions in Haryana.

#### 2.2.1. Hisar (HSR)

Hisar, a suburban city of Haryana is situated at 29.14° N latitude and 75.72° E longitude. It has a mean temperature of 40 °C and 10 °C in pre-monsoon and winter, respectively. It receives a mean annual rainfall of 450 mm. Frequent dust storms are a notable feature of pre-monsoon (Kaushik et al., 2012). Agricultural fields are located ~5 km from its centre. During harvesting, CRB is a regular practice in and around this area.

#### 2.2.2. Karnal (KAR)

Karnal, another suburban city of Haryana is situated at 29.68° N latitude and 76.99° E longitude and has a geographical area of 2520 km<sup>2</sup>.

It has a mean annual rainfall of 544.5 mm (SAH, 2017). Moreover, May and June are the hottest months, while January is the coldest. Agricultural fields are located ~7 km from Karnal and CRB has been a continuous practice in the past few years.

## 3. Data and methods

Hourly PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> concentrations for the selected sites in Delhi and Haryana during 2019 were obtained from the Central Pollution Control Board (CPCB; <http://cpcb.nic.in/real-time-air-quality-data/>) data portal. Meteorological parameters such as ambient temperature (AT), relative humidity (RH), wind speed (WS) and wind direction (WD) were obtained from the Indian Meteorological Department (IMD) as daily means for 2019. Air pollutant data over Haryana was analysed for pre-burning and burning periods of kharif (rice) and rabi (wheat) season. Concurrently, data was collected over Delhi to study the impact of transported air pollutants released from CRB activities in Haryana. The four main periods of the cropping system in 2019 are 1) pre-burning kharif (6<sup>th</sup> September–10<sup>th</sup> October), 2) burning kharif (11<sup>th</sup> October–20<sup>th</sup> November), 3) pre-burning rabi (10<sup>th</sup> March–15<sup>th</sup> April), and 4) burning rabi (16<sup>th</sup> April–21<sup>st</sup> May). These durations are determined based on 1) existing literature, 2) survey information collected from local population and farmers, and 3) satellite-derived fire count and intensity data.

### 3.1. MODIS thermal anomalies

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor is on-board two satellite platforms, viz. Aqua and Terra. For each wavelength (ranging from visible to infrared spectrum) the satellite records digital numbers (DN). DN values from specific wavelength channels can be used to estimate the top of atmosphere radiance, reflectance or brightness temperature. Of its many uses, 4, 11 and 12 μm wavelength channels are used to identify potential fire pixels. The collection 6 algorithm developed by Giglio et al. (2016) uses dynamic day and night-time temperature thresholds to identify potential fires. Compared to the previous collection 5 dataset, dynamic thresholds greatly improve thermal anomalies and fire detection across the globe (Giglio et al., 2016).

For the present study, MODIS Aqua and Terra Thermal Anomalies (at 1 km spatial resolution) data were used to locate active fires over Haryana. This vector (point location) data was acquired from the Fire Information for Resource Management System (FIRMS) database of NASA (<https://firms.modaps.eosdis.nasa.gov/download/>). Collection 6 MODIS thermal anomalies can detect various types of fires, including vegetation burning, active volcanoes and other static fire sources. Supplementary Table 1 shows the number of fire counts for rabi and kharif during the pre-burning and burning period. Of the total fires burning in the selected bounding box over northern India (70–80° E longitude, 25–35° N latitude), only those flagged as biomass/vegetation burning (type 0 in MODIS data) and falling inside the Haryana state boundary were further considered. Following Chandra and Sinha (2016), fire events flagged with the confidence level <80% in the downloaded dataset were rejected and filtered out. The remaining high confidence events (≥80%) were considered for the present study. Location, brightness temperature, day/night fire event and fire radiative power (FRP) is also provided within the dataset.

### 3.2. HYSPLIT model (backward trajectory analysis)

The sources of the air mass were identified using the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory's (ARL) HYSPLIT model. This model is widely used to compute air parcel trajectories as well as the complex transport, dispersion, chemical transformation, and deposition simulations (Draxler and Hess, 1998). Performing backward trajectories from receptor sites is more efficient than forward trajectories, to find potential source locations (Stein et al.,

**Table 1.** Mean of meteorological variables during pre-burning and burning periods of rabi season in Haryana and Delhi.

Haryana				
	Pre-burning (rabi)		Burning (rabi)	
	HSR	KAR	HSR	KAR
AT (°C)	26.2 ± 4.7	25.6 ± 3.1	31.9 ± 3.6	30.2 ± 3.0
RH (%)	47 ± 10	50 ± 9	33 ± 15	35 ± 1
WS (m/s)	1.7 ± 0.5	0.8 ± 0.3	1.8 ± 0.5	0.9 ± 0.3
WD	SW	SW	SW	SW
Delhi				
	Pre-burning (rabi)		Burning (rabi)	
	RKP	IGI	RKP	IGI
AT (°C)	23.6 ± 4.7	25.3 ± 4.3	29.5 ± 3.5	30.8 ± 3.0
RH (%)	43 ± 8	58 ± 10	34 ± 11	50 ± 11
WS (m/s)	0.9 ± 0.3	3.2 ± 2.0	1.0 ± 0.4	3.8 ± 1.2
WD	SW	SW	SW	SW

**Table 2.** Same as Table 1, but for kharif season.

Haryana				
	Pre-burning (kharif)		Burning (kharif)	
	HSR	KAR	HSR	KAR
AT (°C)	28.6 ± 2.2	26.7 ± 4.8	23.8 ± 2.7	22.9 ± 2.2
RH (%)	71 ± 7	74 ± 10	55 ± 7	66 ± 6
WS (m/s)	1.5 ± 0.4	0.5 ± 0.2	1.2 ± 0.5	0.6 ± 0.3
WD	SE	SE	SW	SW
Delhi				
	Pre-burning (kharif)		Burning (kharif)	
	RKP	IGI	RKP	IGI
AT (°C)	26.5 ± 2.3	28.7 ± 2.2	20.6 ± 2.8	22.9 ± 2.5
RH (%)	66 ± 4	74 ± 5	61 ± 5	71 ± 5
WS (m/s)	0.9 ± 0.4	2.7 ± 1.9	0.5 ± 0.2	1.7 ± 0.9
WD	SE	SE	SW	SW

2015; Draxler, 2011). In the present study, three days of NOAA-HYSPLIT air mass back trajectories at 500 m and 1000 m above ground level (AGL) were used to study the air mass movements over the region in rabi and kharif season.

## 4. Results and discussion

### 4.1. Meteorological parameters variations

The variations of meteorological variables viz., AT, RH, WS, and WD during pre-burning and burning periods of rabi (Table 1) and kharif season (Table 2) for Delhi and Haryana are presented. In rabi season, AT varied from 23.6 to 31.9 °C. AT considerably increased from pre-burning (mid-March to mid-April) to burning (mid-April to mid-May) period due to progressing pre-monsoon season (Table 1). RH is lowest (highest) during the burning (pre-burning) period of rabi (kharif) season. RH varied from 33% to 58% in selected sites in Delhi and Haryana. Winds are observed to be considerably stronger (3.8 m/s) over IGI site in Delhi in rabi season as compared to other sites and seasons. Winds in rabi season blow in the southwest direction and do not show any wind reversal from pre-burning to burning period transition (Table 1).

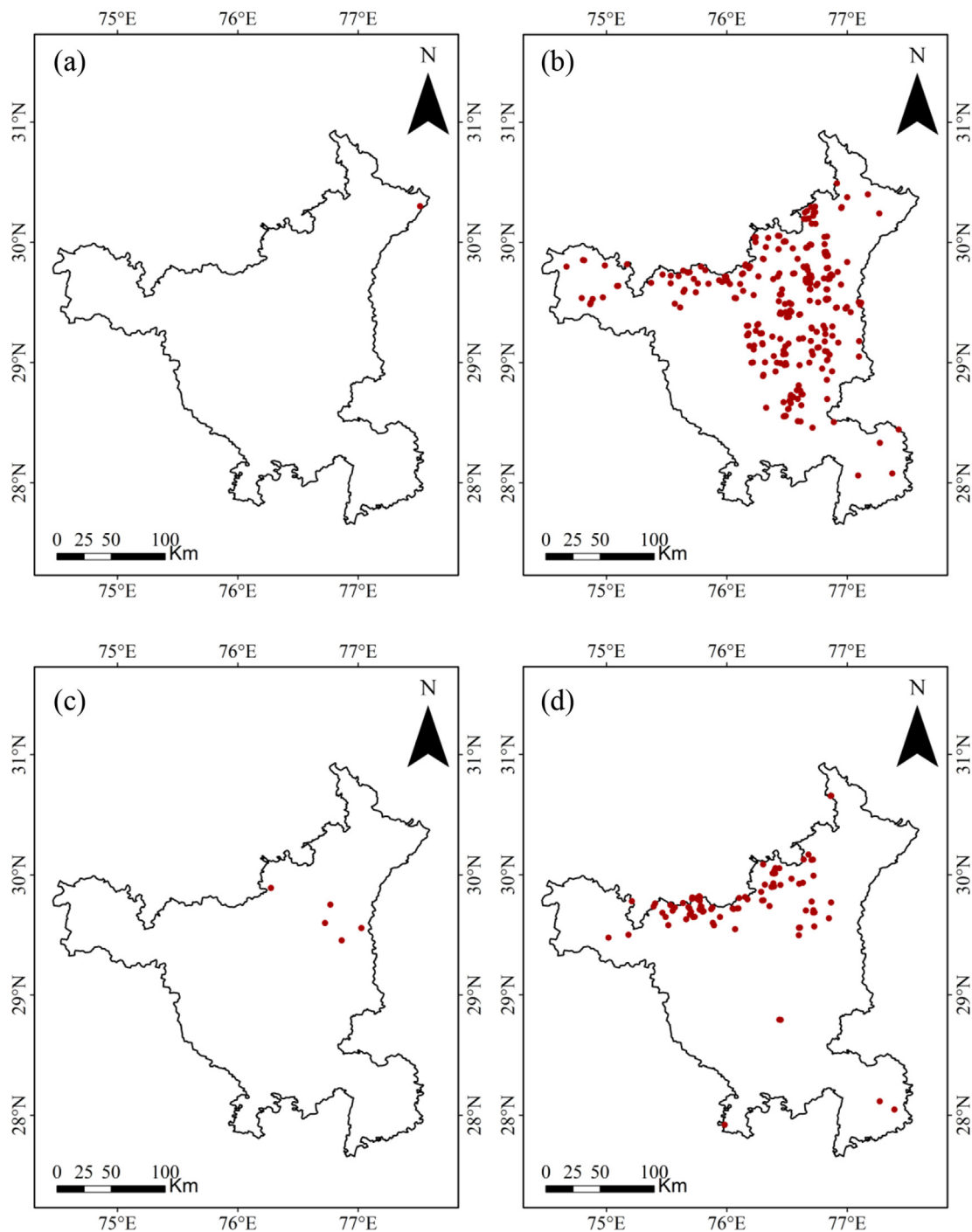
In case of kharif season, AT varied from 20.6 to 28.7 °C. It decreased from pre-burning (mostly September) to burning (mid-October to mid-November) period due to onset of winter (Table 2). Similar pattern is noted for RH. Winds at IGI site during pre-burning period (2.7 m/s) were remarkably stronger than the burning period (1.7 m/s). Unlike rabi season, a wind reversal from southeast (during pre-burning) to southwest

(during burning) direction is noted in kharif season for both Delhi and Haryana (Table 2).

### 4.2. Fire count analysis

CRB fire events extracted from Collection 6 MODIS thermal anomalies dataset are mapped for rabi and kharif seasons (Figure 2). For both, the number of fire counts increase significantly during the burning period. Furthermore, during the pre-burning period of kharif season, only one CRB fire incidence is observed. However, in rabi, 5 such incidences are noted in the pre-burning period (Figure 2 a, c). CRB fires in the rabi season are much higher in number (277 in total) and are more widely spread across Haryana (Figure 2b). Conversely, fire events (90 in total) during the burning period of kharif are mostly restricted near the Punjab-Haryana state border (Figure 2d). Similar observations were reported by Lohan et al. (2018), where, in Haryana alone, rabi contributed to 57.31% and kharif contributed to 21.17% in CRB events. Yadav et al. (2014) noted that the maximum area under rabi CRB (100.05 thousand ha) was higher than kharif (90.84 thousand ha) in most of the agricultural regions of Haryana e.g., KAR, Kurukshetra, Kaithal, etc. Moreover, Jitendra et al. (2017) also reported that straw left rooted to the ground from mechanised farming practices, is later burned in April–May, causing poor air quality in Haryana.

Figure 3 shows daily incidences of CRB events (confidence ≥80%) during rabi season. Daily fire counts significantly increase from the pre-burning period (Figure 3a) to the burning period (Figure 3b). Furthermore, fire counts peak on April 28, after which a decline is noted.



**Figure 2.** CRB fire counts (confidence  $\geq 80\%$ ) during rabi (wheat) season (a) pre-burning period (b) burning period, as well as kharif (rice) season (c) pre-burning period and (d) burning period, for the year 2019, across Haryana.

However, CRB gradually increases during the first week of May, reaching its highest activity on May 9. Interestingly, rabi CRB events were notably restricted from May 4–13. CRB fires in kharif season are increasingly evident after October 10 (Figure 4b). However, few CRB fires are also noted in the late pre-burning period (Figure 4a), indicating earlier harvest by some farmers. While in kharif burning period, CRB fires are consistent (October 12 to November 11). Peak fire activity is observed on November 4, during the latter half of the season. Other than CRB incidences, the radiant heat output, i.e. fire intensity from each event, is also an important parameter (Laurent et al., 2019). Therefore, the parameter FRP is helpful to estimate the pixel-integrated FRP (in megawatts; MW). Since FRP is representative of  $1\text{ km} \times 1\text{ km}$  grids, a higher

FRP could imply 1) a higher quantity of stubble present in that grid for CRB or 2) more radiant heat was generated per kilogram of CRB. Figure 5 shows the frequency distribution of FRP for burning period of both seasons. Fire counts and FRP data over Punjab in rabi and kharif season have also been added as part of supporting information (Suppl. Figures 2, 3, and 4).

For both seasons, majority of CRB fires have  $<100$  MW radiant heat output and most events fall in the 25–50 MW FRP frequency bin. This means that low to medium intensity fires are prevalent during most CRB fire incidences in Haryana. However, rabi season CRB shows stronger FRP ( $>300$  MW for some fires) compared to kharif season CRB.

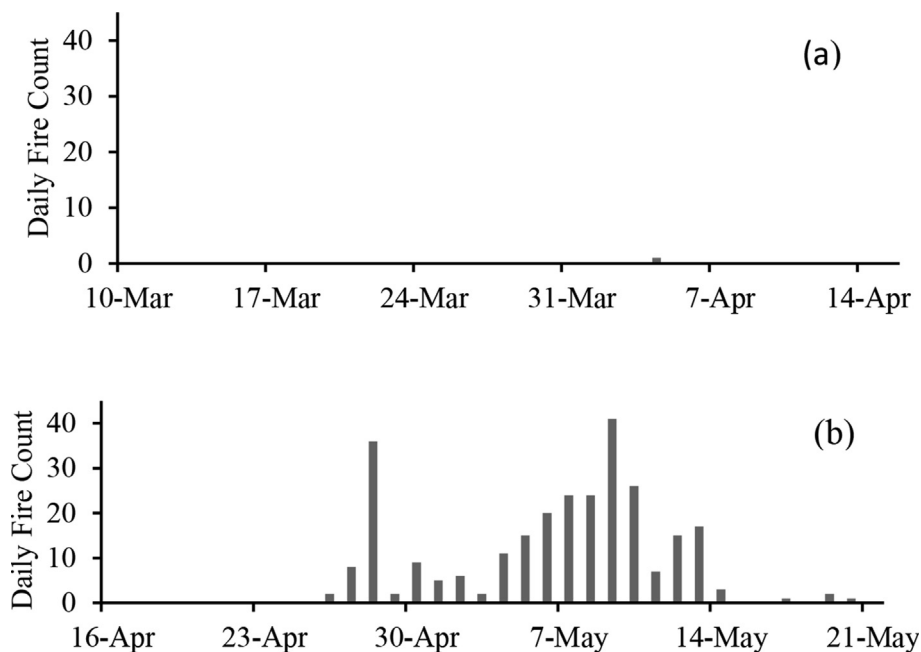


Figure 3. Daily fire counts (confidence  $\geq 80\%$ ) during (a) pre-burning and (b) burning period in rabi season across Haryana in 2019.

4.3. Backward trajectory analysis

Three days NOAA-HYSPLIT air mass backward trajectories were plotted for burning period of rabi (Figure 6 a, b) and kharif (Figure 6 c, d) season. Plots for pre-burning period are provided as part of supplementary information (Suppl. Fig. 5). As high pollutant load and smoke plumes are mainly restricted to the lower troposphere, the trajectory altitudes in the model were set at 500 m and 1000 m. Some studies report the typical height of air masses as 500–800 m, especially during the pre-burning period (Kaskaoutis et al., 2014), whereas others report that the smoke-laden air masses may travel even higher (Badarinath et al., 2009a). Moreover, the HYSPLIT backward trajectory analysis has been extensively used for the detection of the air mass movement (Jethva et al., 2018; Saxena

et al., 2019, 2020a, b; Stein et al., 2015; Badarinath et al., 2009b). By considering Delhi as the sink location, air mass movement could sufficiently link the potential impact of CRB practices in Haryana. Two backward trajectories were plotted for burning period in each season (Figure 6). In rabi season, majority of the air masses reach Delhi from the adjacent state viz., Haryana, and from farther away states such as Punjab (Figure 6 a, b). Air masses also reach Delhi, from Pakistan, a neighboring country to India. Similar to rabi, in kharif season, many air masses reach from Haryana, Punjab and Pakistan, while some air masses from IGP also reach Delhi (Figure 6 c, d).

Pollutants emitted through CRB activities in any of these adjacent or faraway states will reach via the air masses to Delhi and thus deteriorate its air quality.

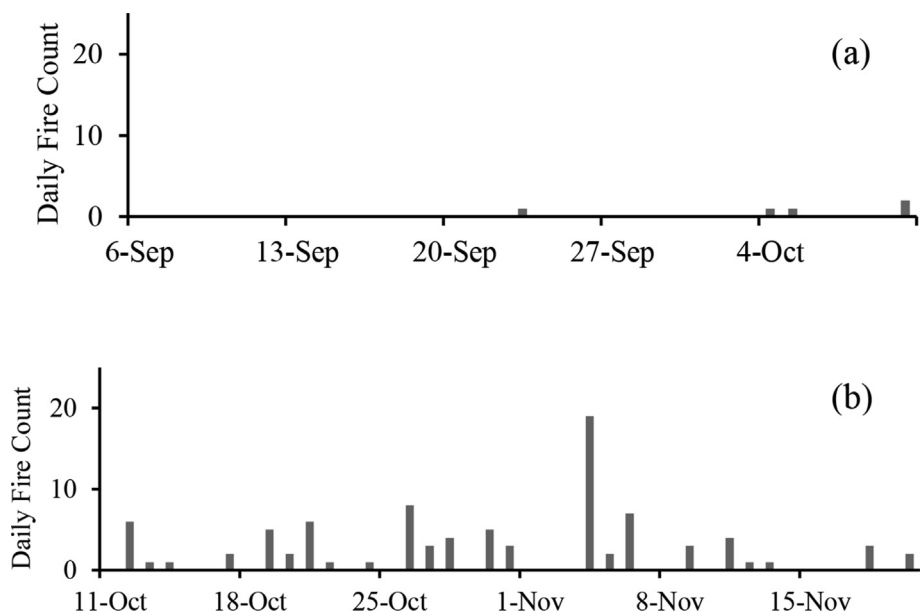
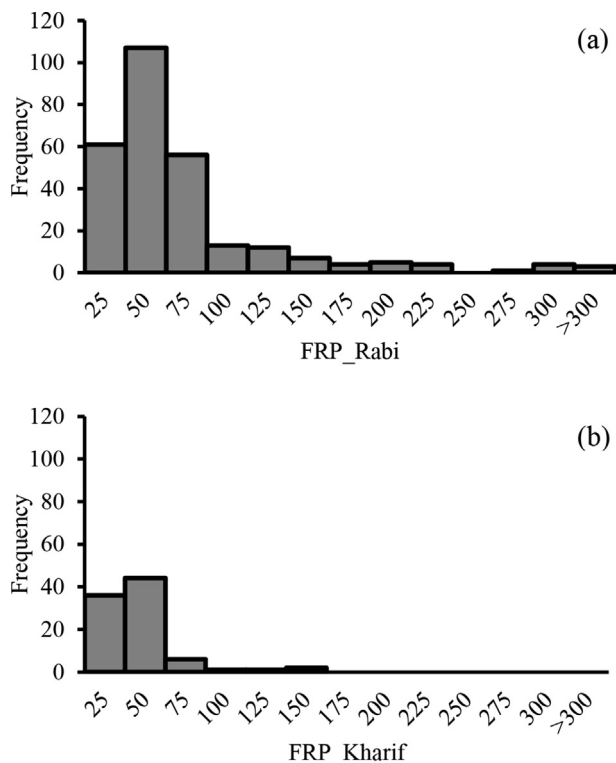


Figure 4. Same as Figure 3, but for kharif season.



**Figure 5.** Frequency distribution of pixel-integrated Fire Radiative Power (FRP; MW) for burning period in (a) rabi and (b) kharif season in Haryana.

#### 4.4. Distribution of $PM_{10}$ , $PM_{2.5}$ , $NO_2$ and $SO_2$

##### 4.4.1. Descriptive statistics

Pre-burning and burning concentration (mean  $\pm$  SD) of  $PM_{10}$ ,  $PM_{2.5}$ ,  $NO_2$  and  $SO_2$  for both seasons over Haryana and Delhi are provided in Table 3. Additionally, box and whisker plots of these pollutants are shown in Figure 7. In case of rabi season, a maximum increase of  $\sim 34\%$  and  $\sim 25\%$  in  $PM_{2.5}$  and  $NO_2$  concentrations, respectively is observed over Haryana from pre-burning to burning period (Table 3). This increase can be associated with rampant stubble burning of wheat crop after harvest. Jain et al. (2014) also reported an increase of 18%, 34%, 25% and 17% in  $PM_{10}$ ,  $PM_{2.5}$ ,  $NO_2$  and  $SO_2$  concentrations in rabi burning period in Haryana. For Delhi, the present study observed a  $\sim 23\%$  increase in  $NO_2$ , while a  $\sim 22\%$  decrease in  $PM_{2.5}$  from the pre-burning to burning period (Table 3). The 24-h National Ambient Air Quality Standards (NAAQS) for  $PM_{10}$ ,  $PM_{2.5}$ ,  $NO_2$  and  $SO_2$  are prescribed as 100, 60, 80 and 80  $\mu\text{g}/\text{m}^3$ , respectively. In rabi season, for both Haryana and Delhi,  $PM_{10}$  and  $PM_{2.5}$  concentrations exceeded their NAAQS limits, while  $NO_2$  and  $SO_2$  remained within the limits (Figure 7 a, b).

The transition from pre-burning to burning period in kharif season also shows a considerable increase in the pollutant concentrations. In Haryana, from pre-burning to burning period, an increase of  $\sim 67\%$ ,  $\sim 59\%$  and  $\sim 53\%$  is observed for  $PM_{2.5}$ ,  $PM_{10}$  and  $NO_2$  respectively while for Delhi, an increase of  $\sim 76\%$ ,  $\sim 66\%$  and  $\sim 19\%$  is observed for the same pollutants (Table 3). Similar to rabi season, in kharif, concentrations of  $PM_{10}$  and  $PM_{2.5}$  exceeded their NAAQS limits, while  $NO_2$  and  $SO_2$  remained within the limits (Figure 7 c, d). Beig et al. (2020) noted high PM concentrations during the kharif burning period in Delhi. Additionally, Chawala and Sandhu (2020) also reported a significant emission of air pollutants through CRB activity. Moreover, pollution load from fireworks during Dusshera (in October) and Diwali (in November) festival contribute towards worsening of air quality in northern India. In the present study,  $PM_{10}$  and  $PM_{2.5}$  concentrations are observed to be several times higher than that of  $NO_2$  and  $SO_2$  (Figure 7). PM can travel long distances as compared to gaseous pollutants (Kim et al., 2015). The

spread of PM from open field CRB activities causes worsening of air quality in the Delhi region (Hays et al., 2005; Sharma et al., 2010; Agarwal et al., 2012; Sidhu et al., 2015). The role of meteorology is crucial in impeding vertical mixing of air masses and dispersion of air pollutants. Low temperature, stable atmospheric conditions lead to low pollutant dispersion during winter which aids in significant rise of PM concentrations in kharif. As a result, the pollutant load is essentially trapped within the boundary layer, and this causes a massive spike in the ambient concentrations over Delhi.

##### 4.4.2. Time series analysis

In general, both seasons show higher pollutant concentrations during the burning period (Figures 8 and 9). For rabi season, significantly higher  $PM_{10}$  and  $PM_{2.5}$  concentrations are observed during the burning period over both Haryana and Delhi (Figure 8). Many isolated peaks are also observed from late March to the beginning of April, and can be associated with the prevalence of increased dust storm activity and the absence of pre-monsoonal precipitation over the region. Such dust storms carry a significantly high load of dust from the Thar Desert to Delhi, and therefore dramatically increase particulate concentrations in the atmosphere. As PM and  $NO_2$  are important markers of biomass burning, high peaks witnessed during the rabi burning period represent CRB activity in Haryana. On most days, the concentration of PM is found to be two to three folds higher than the NAAQS standards (Figure 8). Previous research highlights CRB activities are a significant driver of increase in pollutant concentration (Chandra and Sinha, 2016; Jain et al., 2014; Sharma et al., 2010).

Kharif early pre-burning time in September, coincides with the late-monsoon period and occasional precipitation is observed over northern India. Thus, wet scavenging of atmospheric pollutants can sufficiently lower their concentration in the atmosphere (Sonwani and Kulshrestha, 2019). However, by the late pre-burning period (first week of October), monsoonal activity ceases and an increase in pollutants is observed. Over both Haryana and Delhi,  $PM_{10}$  and  $PM_{2.5}$  concentrations significantly exceed their 24-h NAAQS, while  $NO_2$  and  $SO_2$  concentrations remain within the prescribed limits (Figure 9). In kharif burning period,  $PM_{2.5}$  and  $PM_{10}$  concentrations are 33% and 25% higher over Haryana, than the rabi season. The same in case of Delhi was noted to be 61% and 23%, respectively. Several authors also mentioned the increasing concentration of  $PM_{2.5}$  and  $PM_{10}$  in kharif burning period (Grover and Chaudhry, 2019; Sharma et al., 2010; Jain et al., 2014). Apart from CRB activities, favourable meteorological conditions prevailing in winter, as well as, increased pollution load from Dusshera and Diwali firework celebrations are important factors responsible for deteriorating air quality over the region.

##### 4.4.3. Correlation analysis

Underlying associations are determined between mean concentrations ( $\mu\text{g}/\text{m}^3$ ) of  $PM_{10}$ ,  $PM_{2.5}$ ,  $NO_2$  and  $SO_2$  and meteorological parameters viz., WS, AT and RH (Table 4). Pearson correlation coefficient ( $r$ ), assumes an inherent linear relationship in the data (Jain et al., 2017) and the correlation ranges from strong (1.00–0.50) to moderate (0.49–0.30) to weak (0.29–0.00) (Xie et al., 2015). The correlations for both seasons in Haryana and Delhi are calculated only for the burning period. In Haryana, during rabi season  $PM_{10}$  and  $PM_{2.5}$  have a significant strong negative association with RH and a significant strong positive association with AT. In case of Delhi, both these parameters have a significant strong negative association with RH, but a weak positive association with AT. High AT during pre-monsoon, accompanied by low RH, helps soil particles to loosen up and these can be readily dispersed into the atmosphere, with the slightest winds. Burning of straw left rooted to the ground after harvest leads to poor air quality (Jitendra et al., 2017). In addition to CRB activities, the agricultural fields are highly vulnerable to soil erosion, especially, when left unirrigated. Thus, such PM particles are also available for dispersion. Another phenomenon unique to pre-monsoon over the study region is the aggravated dust load in the air,

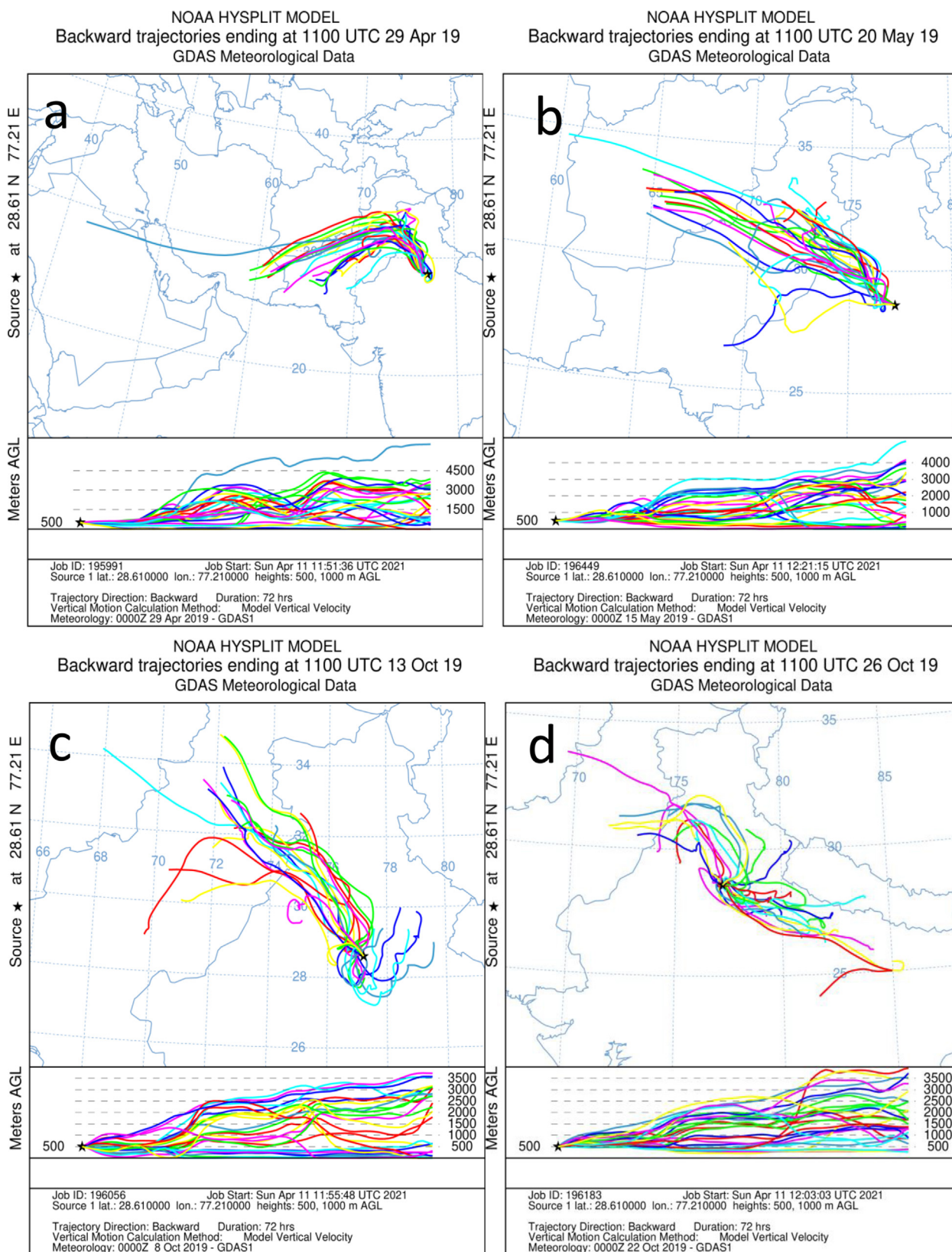
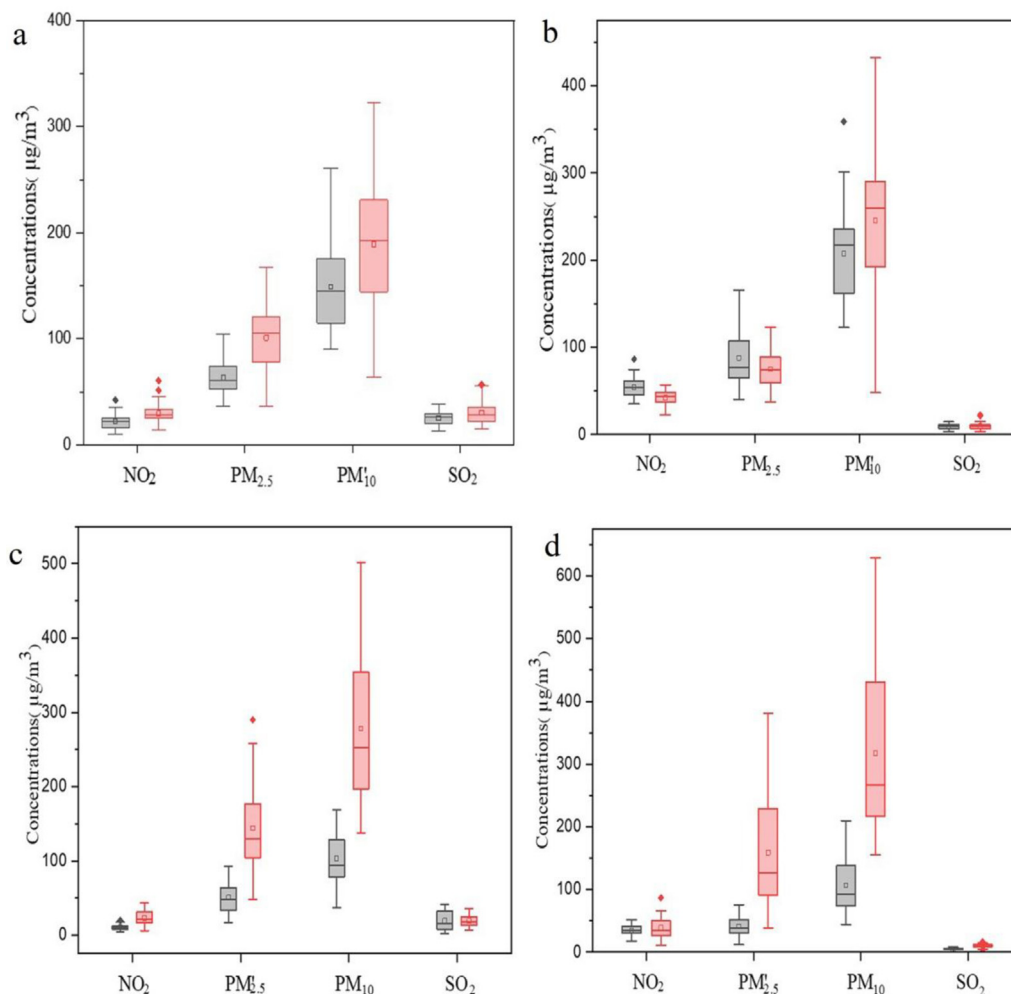


Figure 6. Three day NOAA HYSPLIT backward trajectory analysis plots showing air mass movement to Delhi for burning period in (a, b) rabi and (c, d) kharif season in 2019.



**Table 3.** Descriptive statistics (mean ± SD) of PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> concentrations (µg/m<sup>3</sup>) during the pre-burning and burning period in rabi and kharif seasons at selected sites in Haryana and Delhi.

	Rabi (Pre-burning)						Rabi (Burning)					
	RKP	IGI	Delhi	HSR	KAR	Haryana	RKP	IGI	Delhi	HSR	KAR	Haryana
PM <sub>10</sub>	211.7 ± 50.5	203.6 ± 65.2	207.6 ± 57.5	145.9 ± 50.3	1619 ± 55.0	153.9 ± 52.6	245.8 ± 89.9	245.0 ± 91.3	245.4 ± 90.5	198.4 ± 76.4	180.0 ± 60.3	189.2 ± 68.4
PM <sub>2.5</sub>	101.6 ± 58.7	71.8 ± 23.4	86.7 ± 43.5	64.8 ± 31.6	68.6 ± 27.4	66.7 ± 29.5	61.5 ± 12.3	73.6 ± 33.3	67.5 ± 45.6	98.4 ± 37.8	103.7 ± 32.8	101.0 ± 35.3
NO <sub>2</sub>	73.5 ± 10.1	35.8 ± 18.1	54.6 ± 14.0	22.6 ± 6.8	22.0 ± 11.6	22.3 ± 9.2	71.1 ± 13.8	13.3 ± 2.6	42.2 ± 8.3	28.3 ± 10.3	31.1 ± 12.7	29.6 ± 11.5
SO <sub>2</sub>	9.2 ± 2.5	NA	9.2 ± 2.5	25.6 ± 8.7	25.1 ± 10.4	25.3 ± 9.6	9.8 ± 4.3	NA	9.8 ± 4.3	32.5 ± 12.2	28.4 ± 13.2	30.4 ± 12.5
	Kharif (Pre-burning)						Kharif (Burning)					
	RKP	IGI	Delhi	HSR	KAR	Haryana	RKP	IGI	Delhi	HSR	KAR	Haryana
PM <sub>10</sub>	104.2 ± 44.5	110.5 ± 42.4	107.4 ± 43.2	97.7 ± 30.3	109.3 ± 43.1	103.5 ± 36.5	312.2 ± 125.1	325.9 ± 145.7	319.0 ± 135.0	279.3 ± 113.7	225.6 ± 83.6	252.4 ± 98.5
PM <sub>2.5</sub>	41.5 ± 16.7	40.5 ± 16.7	41.0 ± 16.7	51.4 ± 15.9	50.1 ± 26.9	50.7 ± 21.5	162.6 ± 106.9	187.4 ± 127.1	175.0 ± 117.0	157.3 ± 86.3	150.3 ± 84.8	153.8 ± 85.0
NO <sub>2</sub>	34.6 ± 17.8	34.5 ± 1.6	34.5 ± 10.0	13.2 ± 4.2	8.8 ± 6.6	11.0 ± 10.8	44.7 ± 22.0	40.8 ± 55.4	42.7 ± 38.5	29.1 ± 15.5	17.7 ± 9.2	23.4 ± 12.2
SO <sub>2</sub>	5.2 ± 1.5	NA	5.2 ± 1.5	24.7 ± 14.3	13.9 ± 13.3	19.3 ± 13.8	10.5 ± 2.6	NA	10.5 ± 2.6	20.7 ± 8.1	18.0 ± 6.2	19.4 ± 7.0

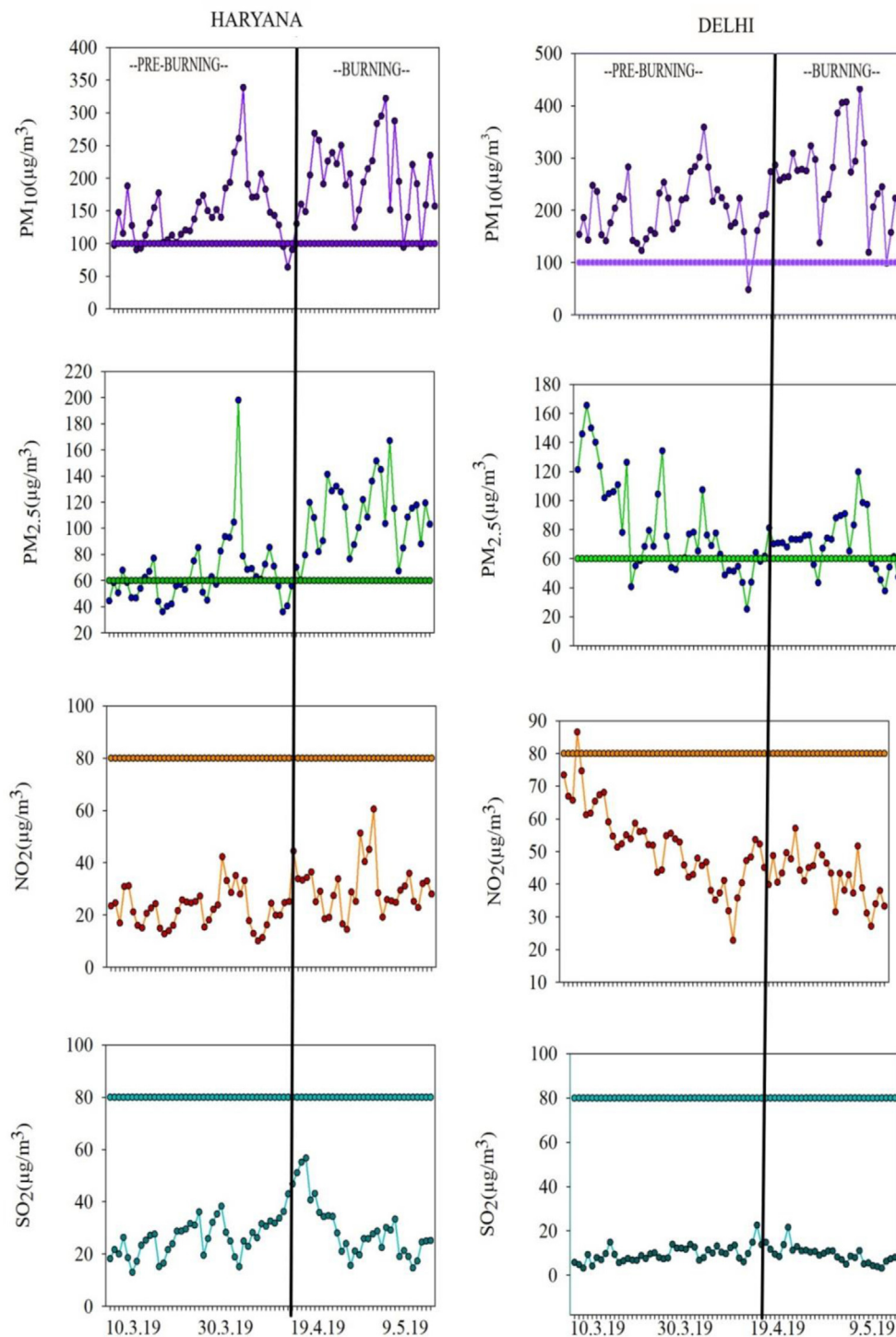


**Figure 7.** Box and whisker plots showing PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> concentrations (µg/m<sup>3</sup>) variations during pre-burning (in grey) and burning (in red) periods, in rabi season in (a) Haryana and (b) Delhi, as well as kharif season in (c) Haryana and (d) Delhi. Plot representations: 75<sup>th</sup> and 25<sup>th</sup> percentiles by box bounds; maximum and minimum by whiskers; 95<sup>th</sup> and 5<sup>th</sup> percentiles by rhombus (solid); median by line (solid) in each box and mean by squares (hollow).

through frequent and intense dust storm activity. All such factors, combined, play a major role in causing high concentrations of PM, when the ambient AT and RH in rabi season, are high and low, respectively. Unlike PM, the emissions of NO<sub>2</sub> and SO<sub>2</sub> are limited in terms of their source. Stronger winds blown over the region in rabi season promote dispersion and/or transport of NO<sub>2</sub> and SO<sub>2</sub>. The same can be noted from Table 4a,b where NO<sub>2</sub> shows a significant strong to moderate, but a negative

correlation with WS over Haryana and Delhi. Interestingly, PM does not show a negative correlation with WS, but in fact is weakly positively associated. This strengthens our point that PM sources are abundantly available, even after possible dispersion via winds.

In kharif season, conditions such as lower AT, higher RH and slower winds exist (Tables 1 and 2). These winter conditions aid in lesser soil erosion from open agricultural fields and low dispersion



**Figure 8.** Time series of PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> during pre-burning and burning periods in the rabi season over Haryana (left panel) and Delhi (right panel). Horizontal lines in each respective sub-plot indicate NAAQS prescribed limits.

of pollutants (Lal et al., 2000; Xie et al., 2015). Table 4 shows that both PM<sub>10</sub> and PM<sub>2.5</sub> have a negative association with AT and WS. This implies that with lower temperature and slow winds, pollutant concentration is increasing or is unable to disperse. In Delhi, PM<sub>10</sub> and PM<sub>2.5</sub> has a significant strong negative association with RH. In both Haryana and Delhi, there exists a significant positive (strong to moderate) association of SO<sub>2</sub> with AT and RH. Again, meteorological conditions in winter exacerbate pollutant concentrations. As expected, NO<sub>2</sub> is significantly strongly negatively associated with AT

in Haryana. However, in case of Delhi, the association is significant, strong but positive. In the year 2019, Delhi government imposed an odd-even scheme from November 4–15, in order to combat the hazardous smog that had enveloped the national capital (Jain et al., 2021). This meant that on any given day the either an odd number plate car could ply, or an even number, thereby significantly reducing the car density and emissions. Thus, meteorological factors also play a role in either increasing or decreasing the pollutant concentrations.

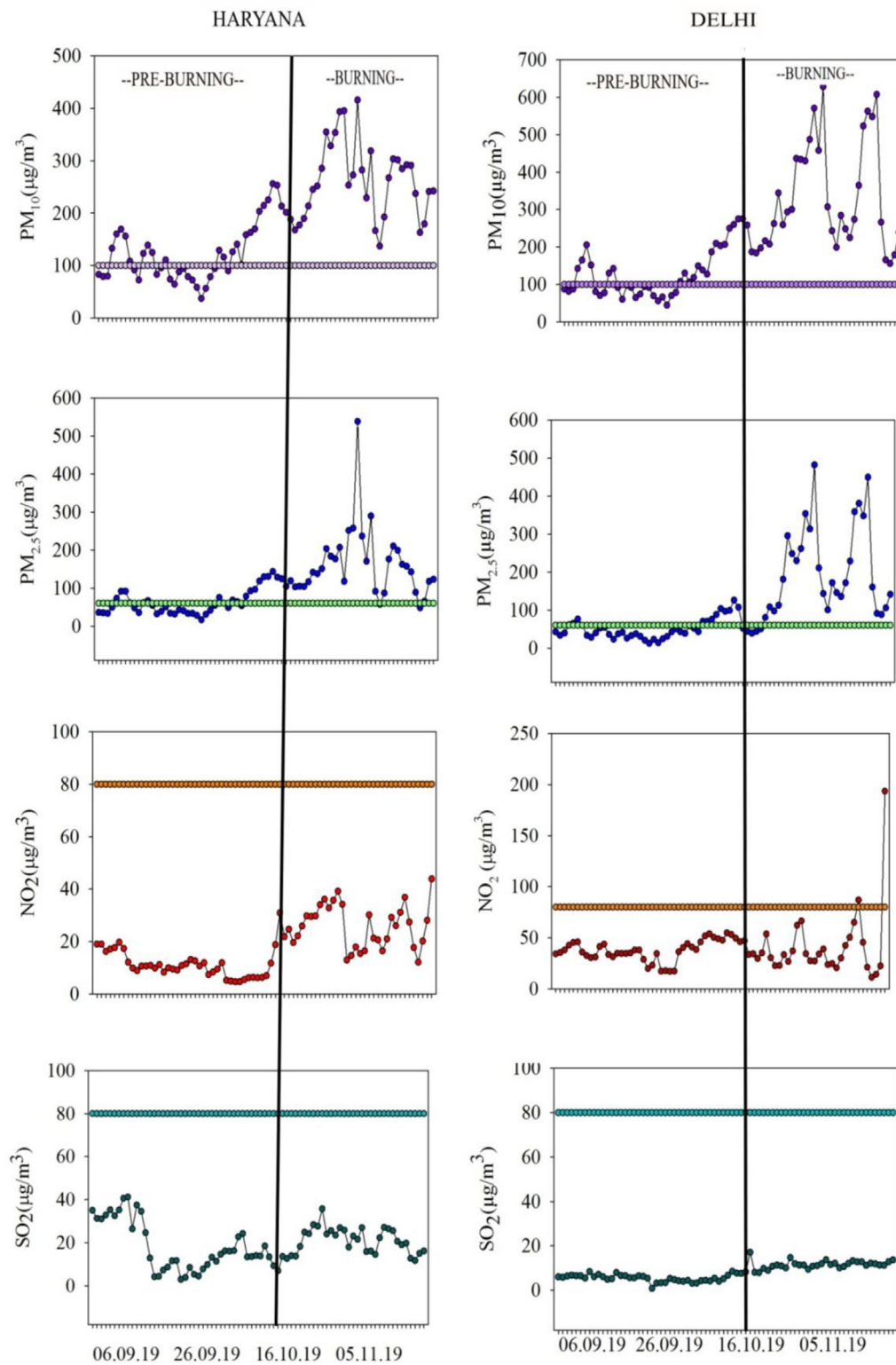


Figure 9. Same as Figure 8, but for kharif season.

### 5. Conclusion

The study highlights the role of Haryana's CRB activities, particularly during rabi season, in deteriorating the air quality of Delhi. CRB fire counts (burning period; confidence  $\geq 80\%$ ) in Haryana are  $\sim 3$  times higher and more intense ( $>300$  MW for some fires) in rabi season

compared to kharif. CRB fires in rabi are evenly spread across Haryana, but are restricted to Punjab-Haryana state border in kharif. Moreover, Yadav et al. (2014) and Lohan et al. (2018) highlight a higher area under CRB in rabi season, as opposed to kharif. Backward trajectories during burning period of both seasons show air mass movement from adjacent state viz., Haryana, and from faraway places such as Punjab and Pakistan.

**Table 4.** Pearson correlation matrix between daily mean concentrations of PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub> and SO<sub>2</sub> and meteorological parameters viz., AT, RH, WS and WD in the burning period of rabi and kharif seasons over Haryana and Delhi.

	NO <sub>2</sub> (µg/m <sup>3</sup> )	SO <sub>2</sub> (µg/m <sup>3</sup> )	PM <sub>10</sub> (µg/m <sup>3</sup> )	PM <sub>2.5</sub> (µg/m <sup>3</sup> )	WS (m/s)	AT (°C)	RH (%)
<b>a. Rabi (Haryana)</b>							
NO <sub>2</sub>	1	-.07	.12	.07	-.37**	.30	-.22
SO <sub>2</sub>	-.07	1	-.00	-.29*	.01	-.25	.02
PM <sub>10</sub>	.12	-.00	1	.79**	.22	.57**	-.55**
PM <sub>2.5</sub>	.07	-.29*	.79**	1	.08	.55**	-.48**
WS	-.37**	.01	.22	.08	1	.13	-.11
AT	.30	-.25	.57**	.55**	.13	1	-.88**
RH	-.22	.02	-.55**	-.48**	-.11	-.88**	1
<b>b. Rabi (Delhi)</b>							
NO <sub>2</sub>	1	.45**	.11	-.14	-.57**	.16	-.47**
SO <sub>2</sub>	.45**	1	.26	.15	-.28	-.26	-.34*
PM <sub>10</sub>	.11	.26	1	.60**	-.01	.32	-.69**
PM <sub>2.5</sub>	-.14	.15	.60**	1	.01	.30	-.56**
WS	-.56**	-.28	-.01	.01	1	.13	.13
AT	.16	-.26	.32	.30	.13	1	.76**
RH	-.47**	-.34*	-.69**	-.56**	.13	.76**	1
<b>c. Kharif (Haryana)</b>							
NO <sub>2</sub>	1	.52**	.07	.13	.03	-.71**	-.49**
SO <sub>2</sub>	.52**	1	.54**	.42**	-.13	-.34*	-.34**
PM <sub>10</sub>	.07	.54**	1	.88**	-.25*	-.09	-.07
PM <sub>2.5</sub>	.13	.42**	.88**	1	-.19	-.07	-.05
WS	.03	-.13	-.25*	-.19	1	-.20	-.26*
AT	-.71**	-.34*	-.09	-.07	-.20	1	.37*
RH	-.49**	-.34**	-.07	-.05	-.26*	.37*	1
<b>d. Kharif (Delhi)</b>							
NO <sub>2</sub>	1	-.33*	.13	.06	-.42**	.50**	.23
SO <sub>2</sub>	-.33*	1	.28	.39*	.02	-.62**	-.00
PM <sub>10</sub>	.13	.28	1	.94**	-.45**	-.22	.57**
PM <sub>2.5</sub>	.06	.39*	.94**	1	-.30	-.43**	.50**
WS	-.42**	.02	-.45**	-.30	1	-.03	-.46**
AT	.50**	-.62**	-.22	-.43**	-.03	1	-.19
RH	.23	-.00	.57**	.50**	-.46**	-.19	1

\* Correlation is significant at the 0.05 level (2-tailed).

\*\* Correlation is significant at the 0.01 level (2-tailed).

Some backward trajectories from IGP, also reach Delhi in kharif season. Pollutants emitted through CRB activities in any of these places reach Delhi via air masses, thus deteriorating its air quality.

The transition from pre-burning to burning period in both seasons showed a considerable increase in the pollutant concentrations. Moreover, PM<sub>10</sub> and PM<sub>2.5</sub> exceeded their NAAQS limits (2–3 times higher), while NO<sub>2</sub> and SO<sub>2</sub> remained within the limits. During late March-early April (i.e., rabi burning period) prevalence of frequent and intense dust storms (high dust load from Thar desert) and the absence of pre-monsoonal precipitation over the region, considerably increases the PM<sub>10</sub> and PM<sub>2.5</sub> concentrations. These pollutants have a significant strong negative association with RH and positive association with AT. High AT during pre-monsoon, accompanied by low RH, loosens up soil particles, especially when left unirrigated. These particles can disperse in the air, with the slightest winds. Unlike PM, the emissions of NO<sub>2</sub> and SO<sub>2</sub> are limited in terms of their source. Stronger winds in rabi season promote dispersion of NO<sub>2</sub> and SO<sub>2</sub>. NO<sub>2</sub> shows a significant strong to moderate, but a negative correlation with WS.

Occasional precipitation is observed in early-September (i.e., onset of kharif pre-burning) and by early-October (i.e., late kharif pre-burning period) monsoonal activity ceases, and an increase in pollutant concentrations is observed. In kharif burning period, PM<sub>2.5</sub> and PM<sub>10</sub> concentrations are 33–61% and 23–25% higher over the region, than rabi season. In kharif season, lower AT, higher RH and slower winds exist.

Both PM<sub>10</sub> and PM<sub>2.5</sub> have a negative association with AT and WS. With lower temperature and slower winds, pollutants are unable to disperse. Apart from CRB activities and favourable meteorological conditions in winter, Dusshera and Diwali firework celebrations is an important factor for deteriorating air quality over the region. As expected, NO<sub>2</sub> has a significant, strong and negative association with AT in Haryana. However, in case of Delhi, the association is significant, strong but positive. This could be due to the impact of the odd-even scheme imposed by the Delhi government from November 4–15, 2019.

Strong initiatives are needed to mitigate the ill-effects of CRB activities over the region, in both rabi and kharif season. Large-scale farmer awareness camps and the use of sustainable CRB management practices are suggested. Moreover, isotopic or marker studies can help the scientific community in analysing the role of rabi CRB emissions coming from Haryana to Delhi and its impacts on air-quality and human health.

#### Declarations

#### Author contribution statement

Pallavi Saxena: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Saurabh Sonwani: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ananya Srivastava, Akash Bharti, Deepali Rangra, Nancy Mongia, Shweta Tejan and Shreshtha Bhardwaj: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Madhavi Jain: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Anju Srivastava: Analyzed and interpreted the data; Wrote the paper.

#### Funding statement

This work was supported by Hindu College, University of Delhi Innovation Project (Ref no. IP-2019-20/SC/13) Grant.

#### Data availability statement

Data associated with this study has been deposited at [www.cb.nic.in](http://www.cb.nic.in) and included in article/supplementary material/referenced in article.

#### Declaration of interests statement

The authors declare no conflict of interest.

#### Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2021.e06973>.

#### Acknowledgements

The authors acknowledge the Central Pollution Control Board (CPCB), Delhi and Haryana State Pollution Control Board (HSPCB) for access to secondary data on air pollutants and meteorological parameters. The authors also thank NASA for the provision of MODIS active fire and thermal anomalies data. Furthermore, the authors are grateful to NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or the READY website (<https://www.ready.noaa.gov>) used in this publication. All data used in this manuscript are available in the public domain and cited in the text. The authors wish to thank the editor and reviewers for their valuable suggestions that will enhance the quality of this manuscript.

#### References

- Agarwal, R., Awasthi, A., Singh, N., Gupta, P.K., Mittal, S.K., 2012. Effects of exposure to rice-crop residue burning smoke on pulmonary functions and oxygen saturation level of human beings in Patiala (India). *Sci. Total Environ.* 429, 161–166.
- Alexaki, N., van den Hof, M., Jol, K., 2019. From Burning to Buying: Creating A Circular Production Chain Out of Left-Over Crop Residue from Indian Farm Land. Netherlands Enterprise Agency, Utrecht, pp. 1–30. Available online at: <https://www.rvo.nl/sites/default/files/2019/12/MVO-Nederland-rapport-India.pdf>.
- Arola, A., Lindfors, A., Natunen, A., Lehtinen, K.E.J., 2007. A case study on biomass burning aerosols: effects on aerosol optical properties and surface radiation levels. *Atmos. Chem. Phys.* 7 (16), 4257–4266. European Geosciences Union, 2007.
- Badarinath, K.V.S., Chand, T.K., Prasad, V.K., 2006. Agriculture crop residue burning in the Indo-Gangetic Plains—a study using IRS-P6 AWiFS satellite data. *Curr. Sci.* 1085–1089.
- Badarinath, K.V.S., Kharol, S.K., Sharma, A.R., 2009a. Long-range transport of aerosols from agriculture crop residue burning in Indo-Gangetic Plains—a study using LIDAR, ground measurements and satellite data. *J. Atmos. Sol. Terr. Phys.* 71 (1), 112–120.
- Badarinath, K.V.S., Kharol, S.K., Sharma, A.R., Prasad, V.K., 2009b. Analysis of aerosol and carbon monoxide characteristics over Arabian Sea during crop residue burning period in the Indo-Gangetic Plains using multi-satellite remote sensing datasets. *J. Atmos. Sol. Terr. Phys.* 71 (12), 1267–1276.
- Beig, G., Sahu, S.K., Singh, V., Tikle, S., Sobhana, S.B., Gargeva, P., Ramakrishna, K., Rathod, A., Murthy, B.S., 2020. Objective evaluation of stubble emission of North India and quantifying its impact on air quality of Delhi. *Sci. Total Environ.* 709, 136126.
- Bhuvaneshwari, S., Hettiarachchi, H., Meegoda, J.N., 2019. Crop residue burning in India: policy challenges and potential solutions. *Int. J. Environ. Res. Publ. Health* 16 (5), 832.

- Chandra, B.P., Sinha, V., 2016. Contribution of post-harvest agricultural paddy residue fires in the NW Indo-Gangetic Plain to ambient carcinogenic benzenoids, toxic isocyanic acid and carbon monoxide. *Environ. Int.* 88, 187–197.
- Chang, D., Song, Y., 2010. Estimates of biomass burning emissions in tropical Asia based on satellite-derived data. *Atmos. Chem. Phys.* 10 (5), 2335–2351.
- Chauhan, A., Singh, R.P., 2017. Poor air quality and dense haze/smog during 2016 in the Indo-Gangetic Plains associated with the crop residue burning and Diwali festival. In: 2017 IEEE International Geoscience and Remote Sensing Symposium, pp. 6048–6051.
- Chawala, P., Sandhu, H.A.S., 2020. Stubble burn area estimation and its impact on ambient air quality of Patiala and Ludhiana district, Punjab, India. *Heliyon* 6 (1), e03095.
- Cheng, Z., Wang, S., Fu, X., Watson, J.G., Jiang, J., Fu, Q., Chen, C., Xu, B., Yu, J., Chow, J.C., Hao, J., 2014. Impact of biomass burning on haze pollution in the Yangtze River delta, China: a case study in summer 2011. *Atmos. Chem. Phys.* 14 (9), 4573–4585.
- Crutzen, P.J., Andreae, M.O., 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. *Science* 250 (4988), 1669–1678.
- Draxler, R.R., Hess, G.D., 1998. An overview of the HYSPLIT\_4 modelling system for trajectories. *Aust. Meteorol. Mag.* 47 (4), 295–308.
- Draxler, R.R., 2011. HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model. Accessed via NOAA ARL ready website. <http://ready.arl.noaa.gov/HYSPLIT.php>.
- Dumka, U.C., Tiwari, S., Kaskaoutis, D.G., Soni, V.K., Safai, P.D., Attri, S.D., 2019. Aerosol and pollutant characteristics in Delhi during a winter research campaign. *Environ. Sci. Pollut. Res.* 26, 3771–3794.
- Gadde, B., Bonnet, S., Menke, C., Garivait, S., 2009. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environ. Pollut.* 157 (5), 1554–1558.
- Giglio, L., Schroeder, W., Justice, C.O., 2016. The collection 6 MODIS active fire detection algorithm and fire products. *Rem. Sens. Environ.* 178, 31–41.
- Grover, D., Chaudhry, S., 2019. Ambient air quality changes after stubble burning in rice-wheat system in an agricultural state of India. *Environ. Sci. Pollut. Control Ser.* 26 (20), 20550–20559.
- Hays, M.D., Fine, P.M., Geron, C.D., Kleeman, M.J., Gullett, B.K., 2005. Open burning of agricultural biomass: physical and chemical properties of particle-phase emissions. *Atmos. Environ.* 39 (36), 6747–6764.
- He, Q., Zhao, X., Lu, J., Zhou, G., Yang, H., Gao, W., Yu, W., Cheng, T., 2015. Impacts of biomass-burning on aerosol properties of a severe haze event over Shanghai. *Particuology* 20, 52–60.
- Jain, N.K., Kaushik, K., Choudhary, P., 2021. Sustainable perspectives on transportation: public perception towards odd-even restrictive driving policy in Delhi, India. *Transport Pol.* 106, 99–108.
- Jain, N., Bhatia, A., Pathak, H., 2014. Emission of air pollutants from crop residue burning in India. *Aerosol Air Qual. Res.* 14, 422–430.
- Jain, M., Dimri, A.P., Niyogi, D., 2017. Land-air interactions over urban-rural transects using satellite observations: analysis over Delhi, India from 1991–2016. *Rem. Sens.* 9 (12), 1283–1297.
- Jethva, H., Chand, D., Torres, O., Gupta, P., Lyapustin, A., Patadia, F., 2018. Agricultural burning and air quality over northern India: a synergistic analysis using NASA's a-train satellite data and ground measurements. *Aerosol Air Qual. Res.* 18, 1756–1773.
- Jethva, H., Torres, O., Field, R.D., Lyapustin, A., Gautam, R., Kayetha, V., 2019. Connecting crop productivity, residue fires, and air quality over northern India. *Sci. Rep.* 9 (1), 1–11.
- Jitendra, Venkatesh, S., Kukreti, I., Pandey, K., Niyogi, D.G., Mukerjee, P., 2017. India's Burning Issue of Crop Burning Takes a New Turn. DTE. Retrieved from: <http://www.downtoearth.org.in/coverage/river-of-fire-57924>.
- Kaskaoutis, D.G., Kumar, S., Sharma, D., Singh, R.P., Kharol, S.K., Sharma, M., Singh, A.K., Singh, S., Singh, A., Singh, D., 2014. Effects of crop residue burning on aerosol properties, plume characteristics, and long-range transport over northern India. *J. Geophys. Res.: Atmospheres* 119 (9), 5424–5444.
- Kaushik, C.P., Sangwan, P., Haritash, A.K., 2012. Association of polycyclic aromatic hydrocarbons (PAHS) with different sizes of atmospheric particulate in Hisar city and its health aspects. *Polycycl. Aromat. Comp.* 32 (5), 626–642.
- Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. *Environ. Int.* 74, 136–143.
- Lal, S., Naja, M., Subbaraya, B.H., 2000. Seasonal variations in surface ozone and its precursors over an urban site in India. *Atmos. Environ.* 34 (17), 2713–2724.
- Langmann, B., Duncan, B., Textor, C., Trentmann, J., van der Werf, G.R., 2009. Vegetation fire emissions and their impact on air pollution and climate. *Atmos. Environ.* 43 (1), 107–116.
- Laurent, P., Mouillot, F., Moreno, M.V., Chao, Y., Ciais, P., 2019. Varying relationships between fire radiative power and fire size at a global scale. *Biogeosciences* 16 (2), 275–288.
- Lohan, S.K., Jat, H.S., Yadav, A.K., Sidhu, H.S., Jat, M.L., Choudhary, M., Peter, J.K., Sharma, P.C., 2018. Burning issues of paddy residue management in north-west states of India. *Renew. Sustain. Energy Rev.* 81, 693–706.
- Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of Lockdown amid COVID-19 Pandemic on Air Quality of the Megacity Delhi, India. *Science of the Total Environment*, p. 139086.
- Mittal, S.K., Singh, N., Agarwal, R., Awasthi, A., Gupta, P.K., 2009. Ambient air quality during wheat and rice crop stubble burning episodes in Patiala. *Atmos. Environ.* 43 (2), 238–244.
- Perrino, C., Tiwari, S., Catrambone, M., Dalla Torre, S., Rantica, E., Canepari, S., 2011. Chemical characterization of atmospheric PM in Delhi, India, during different periods of the year including Diwali festival. *Atmos. Poll. Res.* 2 (4), 418–427.

- Prabhu, V., Soni, A., Madhwal, S., Gupta, A., Sundriyal, S., Shridhar, V., Sreekanth, V., Mahapatra, P.S., 2020. Black carbon and biomass burning associated high pollution episodes observed at Doon valley in the foothills of the Himalayas. *Atmos. Res.* 105001.
- Rana, M., Mittal, S.K., Beig, G., Rana, P., 2019. The impact of crop residue burning (CRB) on the diurnal and seasonal variability of the ozone and PM levels at a semi-urban site in the north-western Indo-Gangetic Plain. *J. Earth Syst. Sci.* 128 (6), 166.
- Saxena, P., Chakraborty, M., Sonwani, S., 2020a. Phytotoxic effects of surface ozone exposure on rice crop—a case study of tropical megacity of India. *J. Geosci. Environ. Protect.* 8 (5), 322–334.
- Saxena, P., Srivastava, A., Tyagi, M., Kaur, S., 2019. Impact of tropospheric ozone on plant metabolism—a review. *Pollut. Res.* 38 (1), 175–180.
- Saxena, P., Srivastava, A., Verma, S., Singh, L., Sonwani, S., 2020b. Analysis of atmospheric pollutants during fireworks festival 'Diwali' at a residential site Delhi in India. In: *Measurement, Analysis and Remediation of Environmental Pollutants*. Springer, Singapore, pp. 91–105.
- Sharma, A.R., Kharol, S.K., Badarinath, K.V.S., Singh, D., 2010. Impact of agriculture crop residue burning on atmospheric aerosol loading—a study over Punjab State, India. *Ann. Geophys.* 28 (2).
- Sidhu, R., Bansal, M., Bath, G.S., Garg, R., 2015. Impact of stubble burning on the ambient air quality. *Int. J. Mech. Prod. Eng.* 3 (10), 46–50.
- Singh, S., Soni, K., Bano, T., Tanwar, R.S., Nath, S., Arya, B.C., 2010. Clear-sky direct aerosol radiative forcing variations over mega-city Delhi. In: *Annales Geophysicae*, 28. European Geosciences Union, pp. 1157–1166. No. 5.
- Sonwani, S., Kulshrestha, U.C., 2019. PM 10 carbonaceous aerosols and their real-time wet scavenging during monsoon and non-monsoon seasons at Delhi, India. *J. Atmos. Chem.* 76 (3), 171–200.
- Statistical Abstract of Haryana (SAH), 2017. Department of Economic and Statistical Analysis, Haryana, pp. 1–707. Publication No. 1180. Accessed online at: <http://esah.haryana.gov.in/en-us/State-Statistical-Abstract-of-Haryana>.
- Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J., Cohen, M.D., Ngan, F., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modelling system. *Bull. Am. Meteorol. Soc.* 96 (12), 2059–2077.
- Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.H., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res.: Atmospheres* 108 (D21).
- Tang, H., Liu, G., Zhu, J., Han, Y., Kobayashi, K., 2013. Seasonal variations in surface ozone as influenced by Asian summer monsoon and biomass burning in agricultural fields of the northern Yangtze River Delta. *Atmos. Res.* 122, 67–76.
- Targino, A.C., Krecl, P., Johansson, C., Swietlicki, E., Massling, A., Coraiola, G.C., Lihavainen, H., 2013. Deterioration of air quality across Sweden due to transboundary agricultural burning emissions. *Boreal Environ. Res.* 18, 19–36.
- Tiwari, S., Srivastava, A.K., Bisht, D.S., Parmita, P., Srivastava, M.K., Attri, S.D., 2013. Diurnal and seasonal variations of black carbon and PM<sub>2.5</sub> over New Delhi, India: influence of meteorology. *Atmos. Res.* 125, 50–62.
- Tsay, S.C., Maring, H.B., Lin, N.H., Buntoung, S., Chantara, S., Chuang, H.C., Gabriel, P.M., Goodloe, C.S., Holben, B.N., Hsiao, T.C., Hsu, N.C., 2016. Satellite-surface perspectives of air quality and aerosol-cloud effects on the environment: an overview of 7-SEAS/BASELInE. *Aerosol Air Qual. Res.* 16 (11), 2581–2602.
- Venkataraman, C., Habib, G., Kadamba, D., Shrivastava, M., Leon, J.F., Crouzille, B., Boucher, O., Streets, D.G., 2006. Emissions from open biomass burning in India: integrating the inventory approach with high-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) active-fire and land cover data. *Global Biogeochem. Cycles* 20 (2), 1–12.
- Wang, Y., Zhang, Q.Q., He, K., Zhang, Q., Chai, L., 2013. Sulfate-nitrate-ammonium aerosols over China: response to 2000–2015 emission changes of sulfur dioxide, nitrogen oxides, and ammonia. *Atmos. Chem. Phys.* 13 (5), 2635.
- Witham, C., Manning, A., 2007. Impacts of Russian biomass burning on UK air quality. *Atmos. Environ.* 41, 8075–8090.
- Xie, Y., Zhao, B., Zhang, L., Luo, R., 2015. Spatiotemporal variations of PM<sub>2.5</sub> and PM<sub>10</sub> concentrations between 31 Chinese cities and their relationships with SO<sub>2</sub>, NO<sub>2</sub>, CO and O<sub>3</sub>. *Particuology* 20, 141–149.
- Yadav, M., Sharma, M.P., Prawasi, R., Khichi, R., Kumar, P., Mandal, V.P., Salim, A., Hooda, R.S., 2014. Estimation of wheat/rice residue burning areas in major districts of Haryana, India, using remote sensing data. *J. Indian Soc. Remote Sens.* 42 (2), 343–352.
- Zhang, H., Hu, D., Chen, J., Ye, X., Wang, S.X., Hao, J.M., Wang, L., Zhang, R., An, Z., 2011. Particle size distribution and polycyclic aromatic hydrocarbons emissions from agricultural crop residue burning. *Environ. Sci. Technol.* 45 (13), 5477–5482.