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Influence of stubble burning on air quality of Northern India: a case study of Indo-Gangetic plains of India

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Abstract Stubble burning is an emerging environmental issue in Northern India, which has severe implications for the air quality of the region. Although stubble burning occurs twice during a year, first during April–May and again in October–November due to paddy burning, the effects are severe during October–November months. This is exacerbated by the role of meteorological parameters and presence of inversion conditions in the atmosphere. The deterioration in the atmospheric quality can be attributed to the emissions from stubble burning which can be perceived from the changes observed in land use land cover (LULC) pattern, fire events, and sources of aerosol and gaseous pollutants. In addition, wind speed and wind direction also play a role in changing the concentration of pollutants and particulate matter over a specified area. The present study has been carried out for the states of Punjab, Haryana, Delhi, and western Uttar Pradesh to study the influence of stubble burning on the aerosol load of this region of Indo-Gangetic Plains (IGP). In this study, the aerosol level, smoke plume characteristics, long-range transport of pollutants, and affected areas during October–November from year 2016 to 2020 were examined over the Indo-Gangetic Plains (Northern India) region by the satellite observations. By MODIS-FIRMS (Moderate Resolution Imaging Spectroradiometer-Fire Information for Resource Management System) observations, it was revealed that there was an increase in stubble burning events with the highest number of events being observed during the year 2016 and then a decrease in the number of events in subsequent years from 2017 to 2020. MODIS observations revealed a strong AOD gradient from west to east. The prevailing north-westerly winds assist the spread of smoke plumes over Northern India during the peak burning season of October to November. The findings of this study might be used to expand on the atmospheric processes that occur over northern India during the post-monsoon season. The pollutant, smoke plume features, and impacted regions of biomass-burning aerosols in this region are critical for weather and climate research, especially given the rising trend in agricultural burning over the previous two decades.

Keywords Biomass burning · Fire points · Air quality · Indo-Gangetic Plains · MODIS

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Introduction

In North-western India, the two major crops that are grown under crop rotation system are wheat and rice (Grover et al., 2016). Further, this region is acknowledged as the "breadbasket" of the country as it generates more than 60 percent of the food grains of the nation (www.outlookindia.com). The Indo-Gangetic Plains (IGP) is a critical agro-ecoregion in southern part of the continent, which incorporates four nations in totality-India, Pakistan, Nepal and Bangladesh (Aggarwal et al., 2004). The IGP possessesapproximately 20% of the geographical area and about 40% of the total population in India while contributing approximately 42% to the total food grains production (Tripathi et al., 2005). As per the Annual Report by Ministry of Agriculture & Farmers' Welfare (2021), rice and wheat crop is cultivated on12 million hectares of land. A recent report by Indian Agricultural Research Institute (IARI, 2012), states that 352 Mt of crop residue is generated each year in India out of which 34% and 22% are contributed by paddy and wheat crop respectively. Further, with great strides in mechanization and rising labor costs, harvesting of these crops with combined harvesters has become very popular among the farmers in Punjab, Haryana and western Uttar Pradesh (Badarinath et al., 2006). However, this has led to surplus quantities of rice and wheat stubble being left behind in the fields which become a hindrance for the next sowing by the farmers (Kumar et al., 2015). Hence, to quickly get rid of the stubble, minimize human labour cost and prepare the field for the next sowing of crops; open burning of stubble in fields is practised in Punjab, Haryana, and parts of western Uttar Pradesh. This has implications for air quality of not only the sites practicing stubble burning, but also the nearby Delhi region, that becomes a "smog chamber" during winter season. The size of the crop area also makes stubble burning a serious problem as more than 17 million tonnes of rice stubble is set to open fire by the farmers each year. This biomass burning is a significant source of pollutants such as PM_{10}, $PM_{2.5}$, SO_x, NO_x, carbon monoxide (CO), methane (CH_4), volatile organic compounds (VOCs), and ozone (Andreae & Merlet, 2001; Pandey et al., 2020). The greenhouse gases like CO_2 and CH_4 directly impact global warming, whereas changes in oxidizing capacity to CO inconsistencies might disturb the development rates of greenhouse gases. Biomass burning is the major cause for thick "brown clouds" in South Asia, especially in the Indo-Gangetic Plains (Gustafsson et al., 2009).Emissions from stubble burning also include black carbon (Gustaffson et al., 2009; Victor et al., 2015) and foster ozone formation by inducing photochemical reactions among its precursor VOCs and NOx (Chen et al., 2016). Besides, since it is well-known that PM_1 constitutes a major portion, i.e., about 85–95% of $PM_{2.5}$; therefore, PM_1 has been studied by Rajput et al. (2018) at an urban location of IGP to understand their abundance and temporal variability. Also, there has been a discernible increment in primary and secondary aerosols, which play a crucial role in atmospheric chemistry and air quality, and have serious impacts on human health. Stubble burning emanates a colossal amount of aerosols which have direct impact as radiative forcing and indirect impact by serving as cloud condensation nuclei (Cattani et al., 2006). Radiative forcing of $+0.04 \pm 0.07$ W m^2 on global scale was reported as contribution from biomass burning aerosols (Forster et al., 2007); subsequently blocking sunlight from coming to the earth's surface and eventually heating the middle and lower troposphere (Kaskaoutis et al., 2014).

Thus, atmospheric pollution is interrelated to stubble burning and has severe consequences at various magnitudes of local, regional, and global scales; and having acute as well as long-term risks to human well-being (Nastos et al., 2010). In recent years, biomass burning in a cultivated landscape has been closely observed through noteworthy developments in geospatial technology as it features a crucial potential in climate change at both regional and global scale.

In Indo-Gangetic Plains, burning agricultural crop residues during the months of October and November is a common practice which leads to accumulation of gases due to negligible dispersion as a result of inversion conditions. During inversion conditions, smoke emitted from stubble burning cannot disperse due to atmosphere being stable, so dilution is reduced that further enhances with fog and leads to the formation of smog. It is pertinent to mention that aerosol properties of hazardous air pollutants are inadequately understood (Mukai, 2018). The emissions of aerosols is an outcome of not only severity and duration of fires, but also the mixing process, dilution, boundary layer dynamics, and meteorological conditions (Chen et al., 2016; Mielonan et al., 2013; Kahn et al., 2007). Primary and secondary pollutants released by stubble burning coupled with automobile exhausts under conditions of high relative humidity (40–70%), light winds (1–2 m/s), and temperatures of 20–30 °C further aggravate the haze over IGP region (Chen et al., 2016; Chawala & Sandhu, 2020). In urban regions, interaction between automobiles/industrial exhausts and smoke plumes of stubble burning augments the formation of secondary inorganic particles (Wang et al., 2015). The present study was carried out to examine aerosol levels, smoke plume characteristics, long-range transport of pollutants, and affected areas during October–November from 2016 to 2020 over the Indo-Gangetic Plains (IGP) region by satellite observations.

Materials and method

Study area

The present study deals with the crop residue burning issue in the Indo-Gangetic Plain (IGP) region. Therefore, for the present study, the states of Punjab, Haryana, Capital city of Delhi and western Uttar Pradesh were the regions taken under consideration (Fig. 1); as paddy stubble burning is practised in these states of India where the fields are cleared for sowing of rabi crops. The state of Punjab (31.05°N,75.35°E) is primarily an agricultural state, lying in north-western parts of India. The state of Haryana (30.30°N, 74.60°E) has agricultural regions adjoining Punjab; and industrial and commercial cities adjoining the national capital city of Delhi (28.61° N, 77.21° E). Further, the western part of the state of Uttar Pradesh also contributes significantly to stubble burning. All these states fall under the Indo-Gangetic Plains (IGP) of India, and were chosen for the present study due to their significant contribution to stubble burning.

Methodology

In this study, the first step was to prepare land use land cover (LULC) map of the study area for the year 2016 and 2020 using supervised classification scheme following Maximum Likelihood Classification (MLC) algorithm in ArcGIS 10.7 software. Landsat-8 OLI datasets for the year 2016 and 2020 were used for the supervised

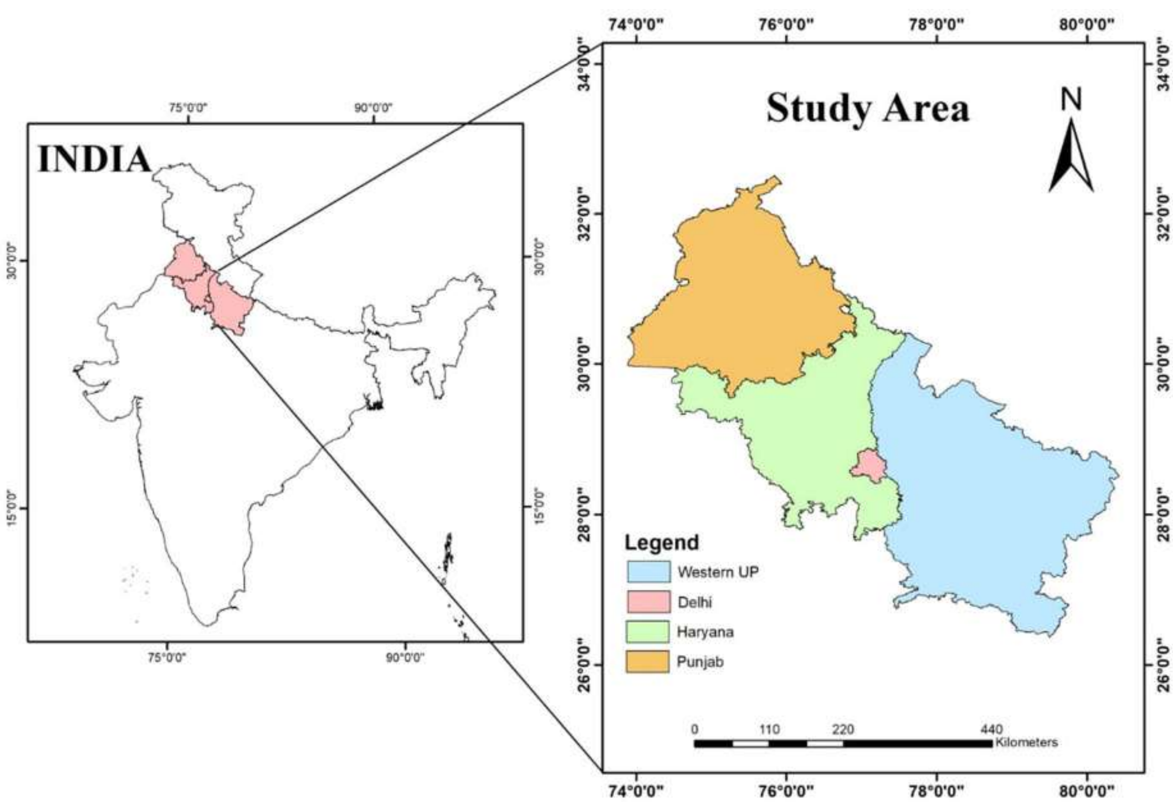


Fig. 1 Study Area of Indo-Gangetic Plains (IGP)

classification using ArcGIS10.7 software. The accuracy assessment was carried out using the following algorithm:

Users accuracy = number of correctly classified pixels in each category/total number of classified pixels in that category (the row total) × 100.

Producer accuracy = number of correctly classified pixels in each category/total number of reference pixels in that category (the column total) × 100.

Overall accuracy = total number of correctly classified pixels (diagonal)/total number of reference pixels × 100.

Kappa coefficient (T) = (TSX TCS)—Σ(Column Total X Row Total)/TS^2—Σ(Column Total—Row Total) × 100.

The biomass burning patterns through active fire points and total burnt area in these states were studied over last 5 years using FIRMS (Fire Information for Resource Management System) and MODIS (Moderate Resolution Imaging Spectroradiometer) data of NASA (earthdata.nasa.gov archives). The NASA MODIS, which is onboard the Terra (descending 10:30 a.m.) and Aqua (ascending 1:30 p.m.), is a 36-channel imager. MODIS has 2 channels with a resolution of 250 m, 5 channels with a resolution of 500 m, and 29 channels with a resolution of 1000 m, with a viewing swath of 2330 km that features a function for fire monitoring. MODIS is the most commonly used sensor in biomass burning research since it as developed to gather worldwide observations of aerosols with a moderate resolution of 250 to 1000 m. The active fire detection algorithm was allocated into two modules: day and night-time.

Aerosol load in the atmosphere for the last 5 years of the study region were studied by using TERRA & AQUA MODIS data for the months of October and November. MODIS (giovanii.gsfc.nasa.gov/giovanni) was used to analyse the aerosol load. NASA's OMI/Aura Near UV Aerosol Optical Depth and Single Scattering Albedo L3 1 day 1.0-degree × 1.0-degree V3 (OMAERUVd) product (grid of 1 deg Lat/Lon), a level-3 daily global girded product at 550 nm, was used in finding aerosol optical depth (AOD). The OMAERUVd product is created by averaging all data pixels that fall within a grid box using pixel level OMI level-2 aerosol data. At three wavelengths, the OMAERUVd data output comprises extinction and absorption optical depths (355 nm, 388 nm, and

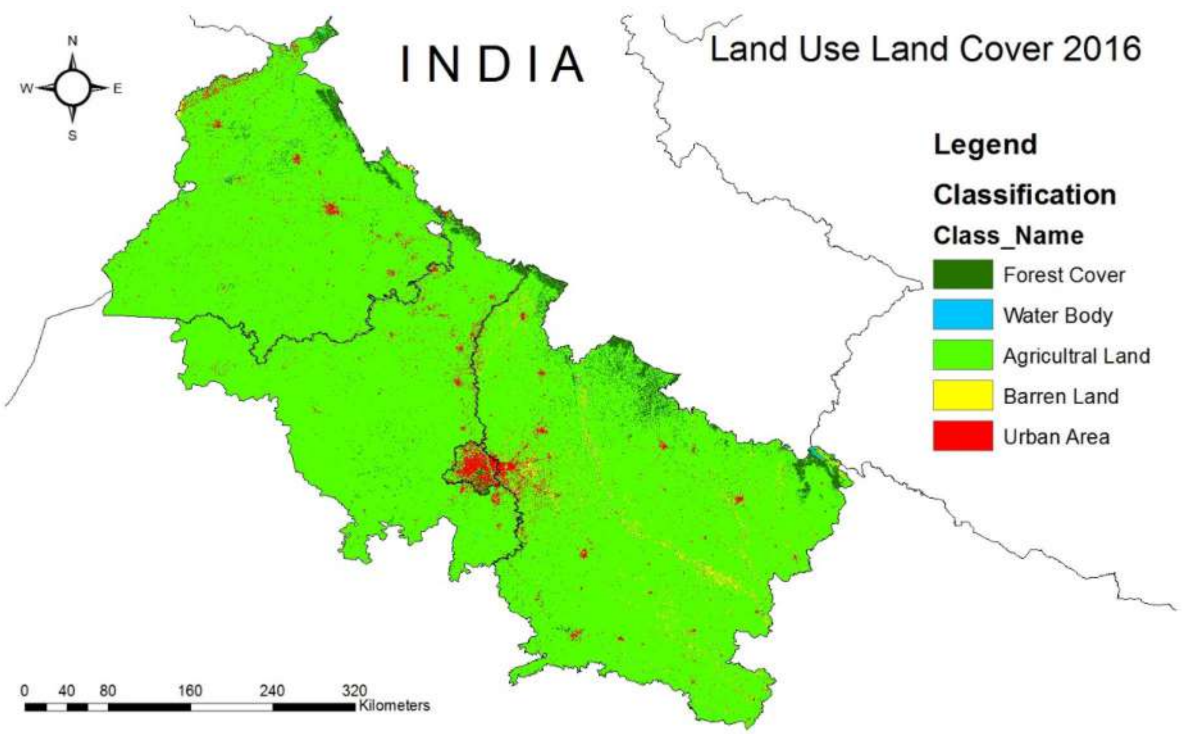


Fig. 2 Land use land cover map of IGP for 2016

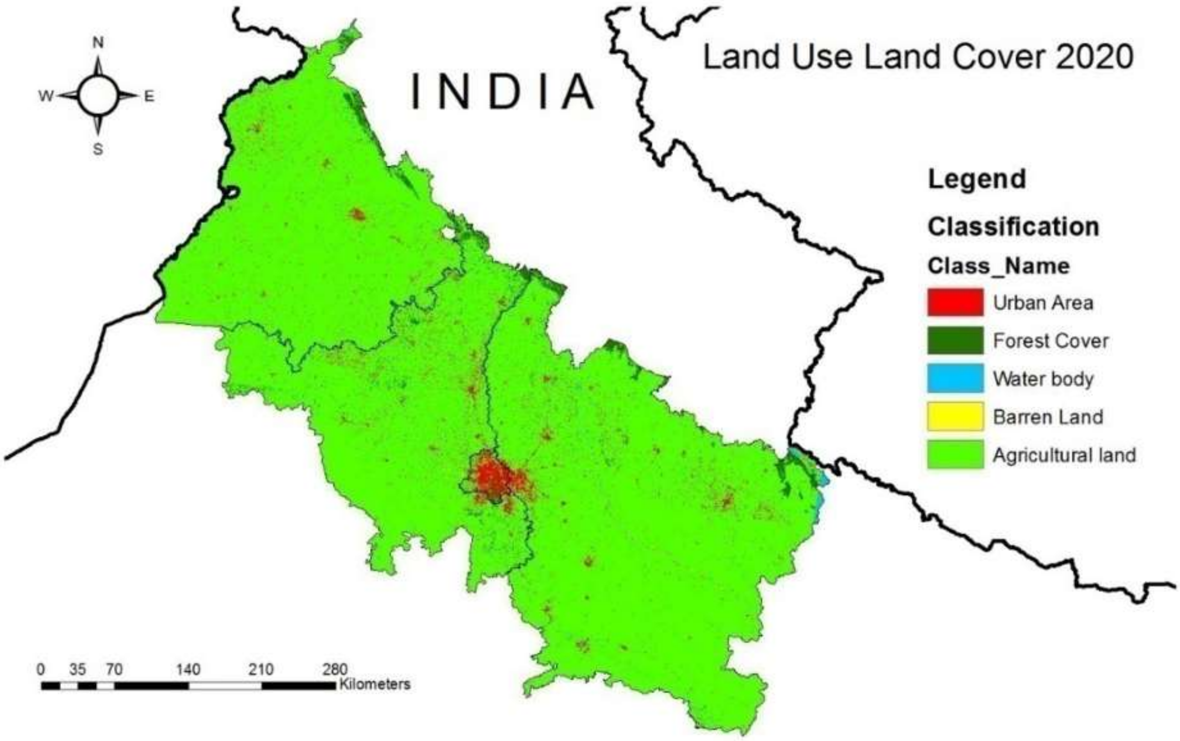


Fig. 3 Land use land cover map of IGP for 2020

500 nm). Further, wind trajectories to study the plume behaviour of these emitted were studied using the HYSPLIT model.

The data pertaining to air quality of the study region was procured from Central Pollution Control Board (CPCB) that provides air quality data at various locations of India (https://cpcb.nic.in/). Also, it is important to mention that $PM_{2.5}$ data of 2016 was unavailable for Punjab. PM_{10} data was missing for Punjab and Haryana for the years 2016 and 2017; while it was missing for 2016 for UP. Further, NO_x, SO_x, CO, and ozone data was missing for the year 2016 for the state of Punjab. Further, the wind trajectory has been plotted using HYSPLIT model procured from (https://www.ready.noaa.gov/hypub-bin/trajtype.pl).

Table 1 Accuracy assessment for LULC map of 2016

S.No.	Water body	Agricultural land	Urban area	Forest cover	Barren land	Total	User's accuracy (%)
Water body	18	2	0	0	0	20	**90**
Agricultural land	0	24	0	0	1	25	**96**
Urban area	0	0	23	0	2	25	**92**
Forest cover	0	0	0	10	0	10	**100**
Barren land	0	2	0	0	8	10	**80**
Total producer	18	28	23	10	11	90	
Producer's accuracy (%)	**100**	**85.71**	**100**	**100**	**72.72**		

Overall accuracy = 92.22%

Kappa coefficient = 0.899

Table 2 Accuracy assessment for LULC map of 2020

S. No.	Water body	Agricultural land	Urban area	Forest cover	Barren land	Total	User's accuracy (%)
Water body	20	0	0	0	0	20	**100**
Agricultural land	0	28	0	0	1	29	**96.55**
Urban area	0	0	20	0	1	21	**95.23**
Forest cover	0	0	0	9	1	10	**90**
Barren land	0	2	0	0	8	10	**80**
Total	20	30	20	9	11	90	
Producer's accuracy (%)	**100**	**93.33**	**100**	**100**	**72.72**		

Overall accuracy = 94.44%

Kappa coefficient = 0.927

Results and discussion

Land use land cover (LULC) maps of Study area

To assess the effect of biomass burning, land use land cover (LULC) maps of the study area were prepared using supervised classification method for the years 2016 (Fig. 2) and 2020 (Fig. 3) respectively.

After classification, accuracy assessment for the years 2016 (Table 1) and 2020 (Table 2) respectively was performed.

The accuracy assessment for the study area showed an overall accuracy of 92.22% and 94.44% for the years 2016 and 2020 respectively (Tables 1 and 2). Kappa coefficient for the year 2016 was 0.899 and for 2020, it was 0.927. The supervised classification of Punjab, Haryana, Delhi and Western UP revealed that agricultural area was the dominant LULC class feature in Punjab, Haryana and Western UP while Delhi was dominated by urban areas. Area under agricultural fields slightly increased in Punjab and Western UP while in Haryana and Delhi Capital region,

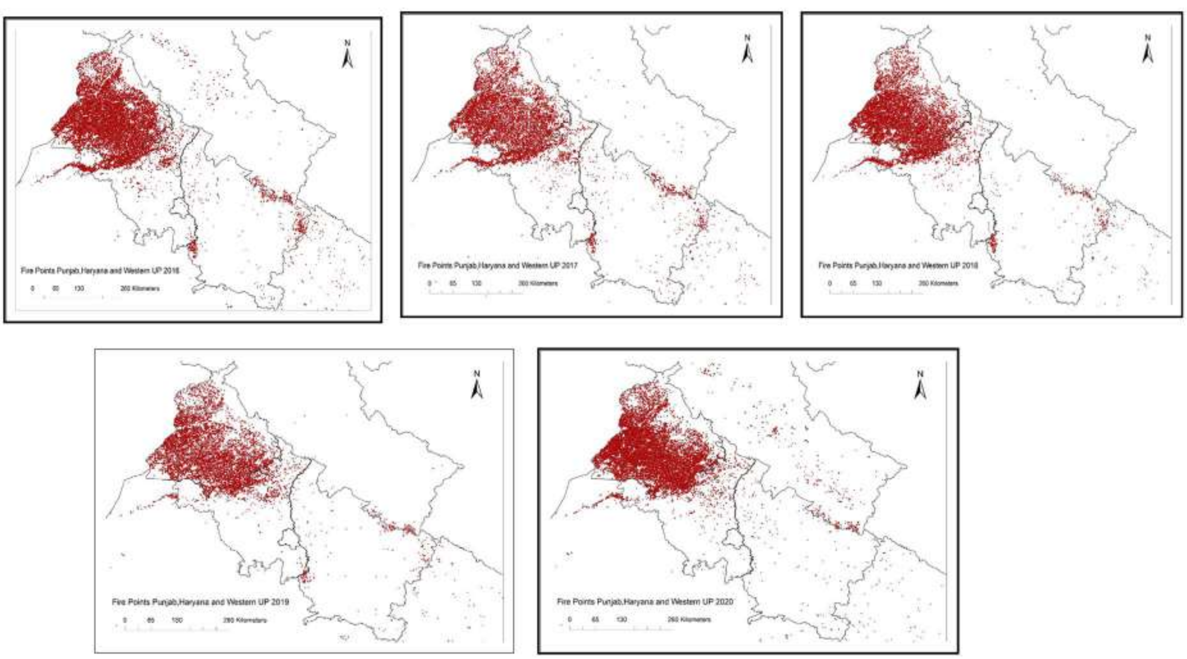


Fig. 4 Active fire points in the study region

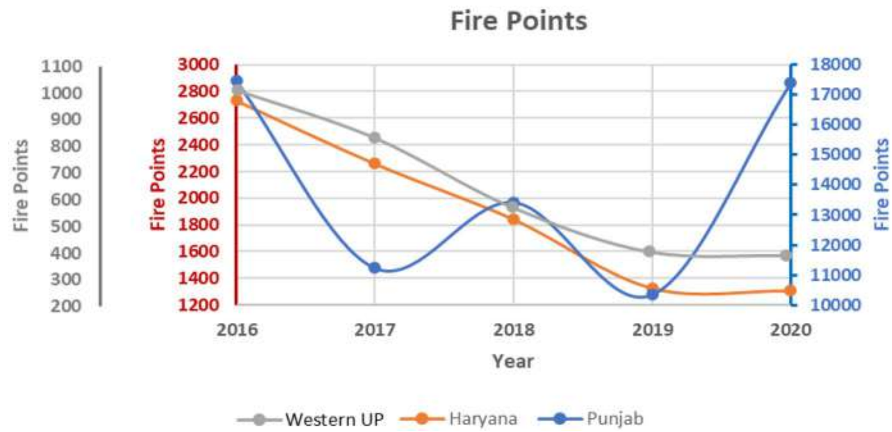


Fig. 5 Fire counts in Punjab, Haryana, and Western UP

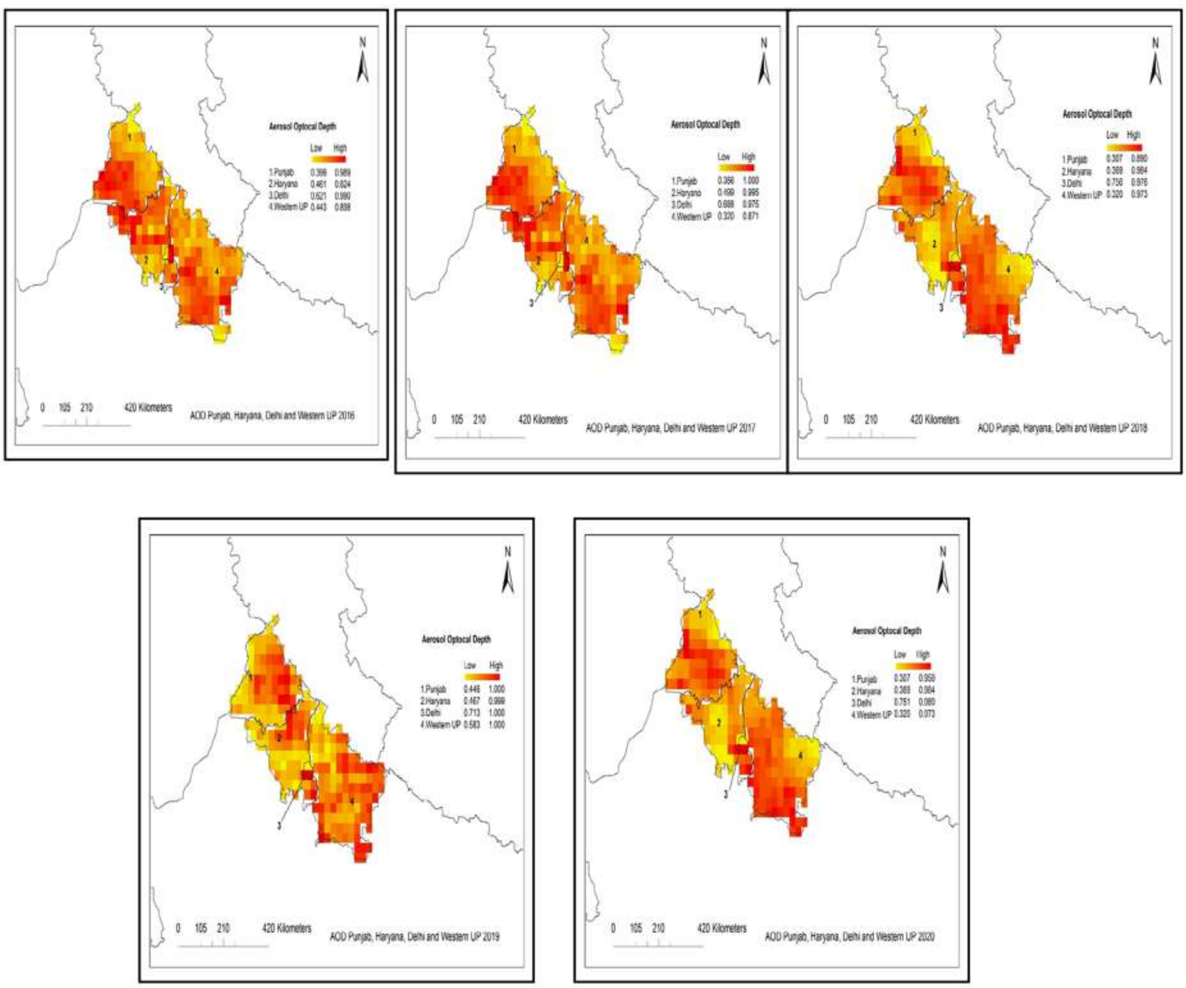


Fig. 6 AOD load for the Indo-Gangetic Plains (IGP) from 2016 to 2020

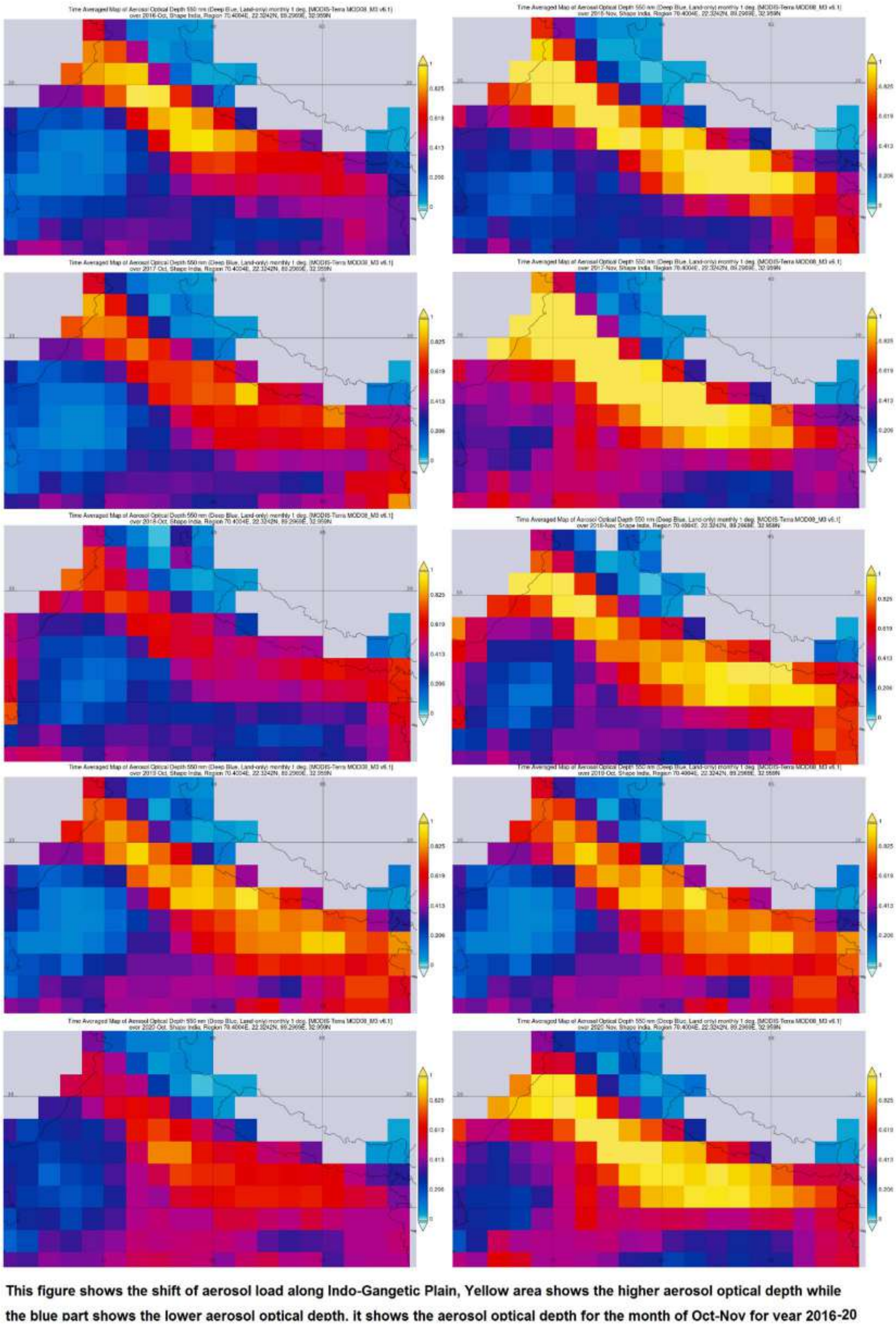


Fig. 7 Shift of aerosol load over IGP from 2016 to 2020

it showed a decreasing trend. The utilisation of land for settlement increased in all the four states; but in Haryana and Delhi, it increased significantly while in case of Punjab and Western UP- it was raised slightly. Forest cover in Punjab and Western UP decreased due to conversion of that land either into urban area or for agricultural purpose. Barren land showed its dominance in Haryana and Delhi as the latter showed an increasing trend during these years which could be the result of rapid urbanisation and population growth. Due to implementation of construction of canal networks, there is a significant increase in water bodies in all these four regions. In Delhi-NCR area, a clear increase in urban areas has been observed from the year 2016 to 2020.

Active fire points

The active fire points obtained from MODIS Thermal Anomalies from the NASA Fire Information for Resource Management System (FIRMS) has been shown in Fig. 4.

Further, the fire counts for the study region have been depicted in Fig. 5 which indicates that the fire counts in Punjab revealed an irregular trend and decreased from 2016 onwards. However, in Haryana and western UP, a continuous decrease in fire counts was observed from 2016 to 2020.

AOD distribution

Aerosol optical depth (AOD)

An analysis of the distribution of aerosol optical depth (AOD) over IGP region (Fig. 6) reveals that the value of AOD was highest for Delhi and variable for Punjab, Haryana and western Uttar Pradesh for all five years respectively. The lowest value of AOD was 0.307 for Punjab, 0.369 for Haryana, 0.621for Delhi and 0.320 for western Uttar Pradesh while the maximum value of AOD was higher than 0.9 in all the states under consideration (Fig. 6) during 2016–2020.

Further, besides studying the AOD over IGP region, an attempt was made to assess the shift in aerosol load from 2016 to 2020 in the Indo-Gangetic Plains (IGP) as observed in Fig. 7. Yellow area shows the higher aerosol optical depth while the blue part shows the lower aerosol optical depth. This shift of aerosol load can be clearly seen in northern India from west to east over Punjab, Haryana, Delhi-NCR, and Uttar Pradesh. MODIS observations revealed a strong AOD gradient from west to east and also it shows the shift during months of October, November and December. As this event occurs during winter, the meteorology of this area plays a role in slow dispersal of pollutants over northern

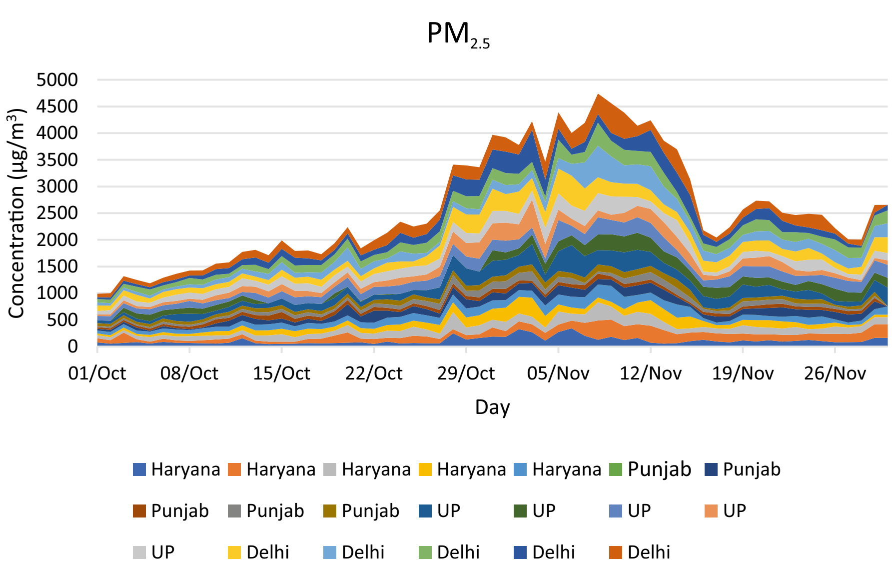


Fig. 8 Concentration levels of $PM_{2.5}$ from 2016 to 2020 in IGP

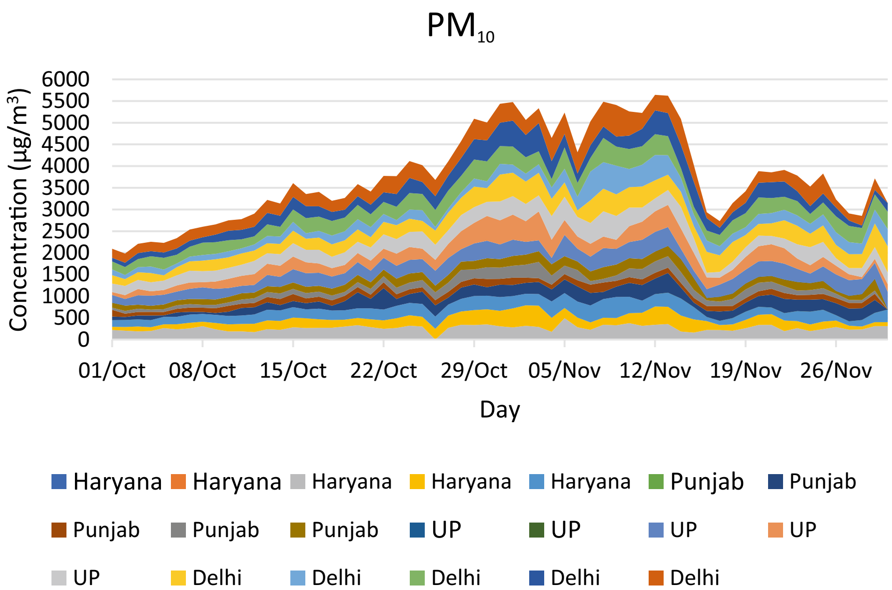


Fig. 9 Concentration levels of PM_{10} from 2016 to 2020 in IGP

India. This shift from west to east in IGP would have a significant impact on air quality of the region depending on meteorological dynamics of the region.

Air quality

In the present study, besides studying the LULC, fire counts and aerosol load, an attempt was made to study the impact of crop residue burning on the air quality of Indo-Gangetic Plains (IGP). The Central Pollution Control Board (CPCB) provided data on ambient air quality for the relevant research period (for the years 2016 and 2020) during the crop residue burning months of October and November. Figures 8, 9, 10, 11, 12, 13, and 14 depict the distribution of various air pollutants during stubble burning season of October and November from 2016 to 2020.

On analyzing the Figs. 8 and 9 regarding $PM_{2.5}$ and PM_{10} concentrations, it becomes evident that a significant increase in $PM_{2.5}$ and PM_{10} levels was observed

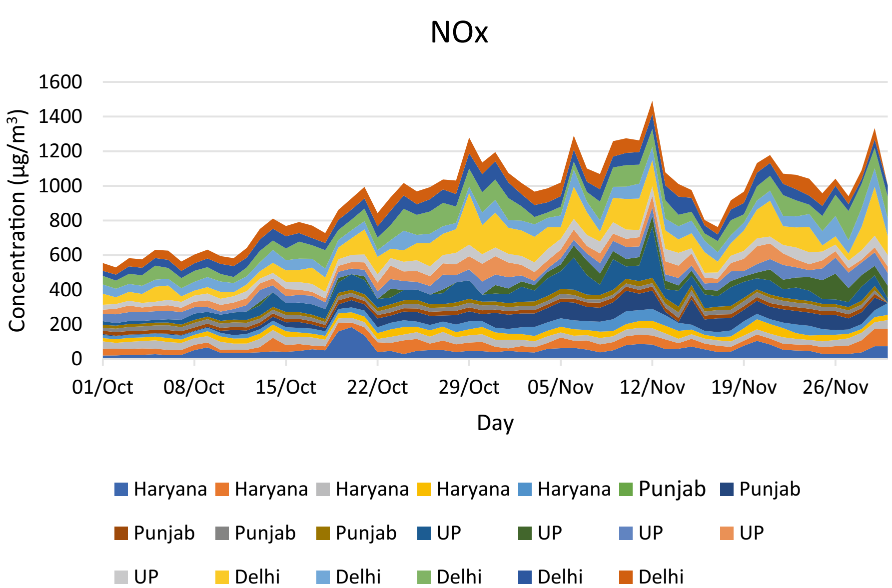


Fig. 10 Concentration levels of NOx from 2016 to 2020 in IGP

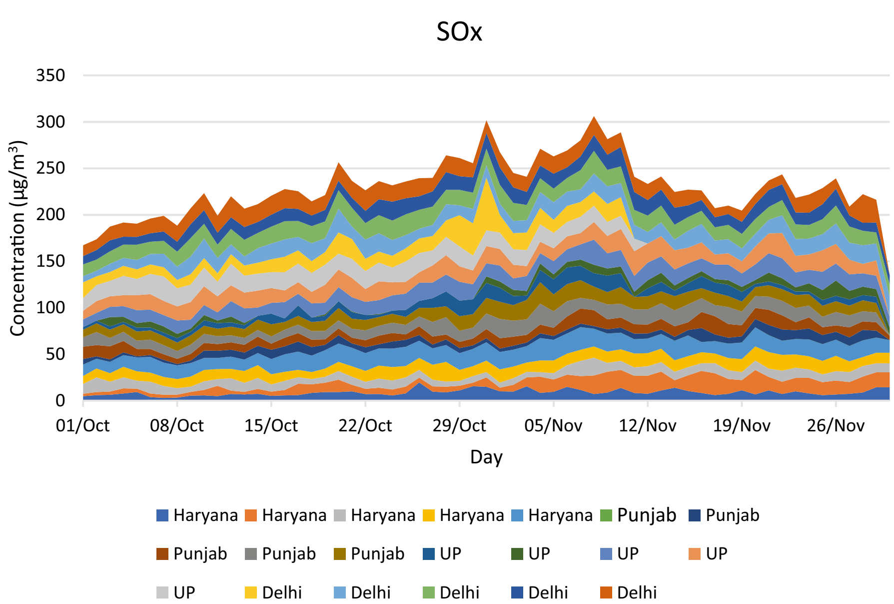
starting from the month of October. As a result, a significant portion of northern and north-western India gets covered by the smoke plumes caused by biomass burning (Figs. 8 and 9). Further, it can be inferred that peak for the $PM_{2.5}$, PM_{10}levels was observed during second week of November (8th–15th November) during 2016–2020. Concentration of $PM_{2.5}$and PM_{10} rose significantly during first two weeks of November and started declining gradually from the last week of November. High particulate matter concentration during these two months is the main reason for haze formation and lowering visibility in whole of the studied area. The results are in agreement with the findings of Bond et al. (2004) who stated that the main component of smoke is organic aerosol which increases during burning event and travels along the wind which further produces the secondary aerosols. Alvarez-Mendoza et al. (2019) used Landsat-7 ETM+, Landsat-8 OLI/TIRS, and Aqua-Terra/MODIS sensors and a few indices such as vegetation, soil and water index besides land surface temperature (LST) to estimate the concentration of PM_{10} using an empirical land use regression (LUR) model in Quito, Ecuador. The models were able to estimate PM_{10} in regions with limited access to air quality data.

Also, a fall in concentration levels just after the peak was observed because of precipitation on 15th, 16th, and 17th November, 2020 (due to retreating monsoon) with average wind speed that was comparatively higher than other days. It is pertinent to mention that the highest pollution level in the year 2020 was observed on 9th of November, a week before Diwali, which indicates that the role of emissions from burning of firecrackers during Diwali celebrations, a religious festival in India, is not very substantial. Further, a single day would not contribute to peak concentrations; however, every year, the stubble burning and burning of fire crackers more or less coincides, thus exacerbating the air quality issue.

The concentration levels of Nitrogen oxides (NOx) have been depicted in Fig. 10, which shows a peak and valley configuration with high concentration levels during mid of November during 2016–20. Further, NOx is considered as precursor for tropospheric Ozone formation (Seo et al., 2014; Nguyen et al., 2022) and its concentration increases due to vehicular emission in urban areas; however, this increase is also observed during biomass burning season (Fig. 10).

As all of the pollutant monitoring stations under consideration are located in major cities such as Delhi where dominant source of SO_2 emission is due to fossil fuel burning in industries and vehicles; but during stubble burning period, it was noticed that for these two months, the level of SO_2 remains higher than the other months (Fig. 11). The peak was observed either during the first or second week of November in all the four regions from the year 2016 to 2020 coinciding with the burning period. Elevated levels of SOx

Fig. 11 Concentration levels of SOx from 2016 to 2020 in IGP



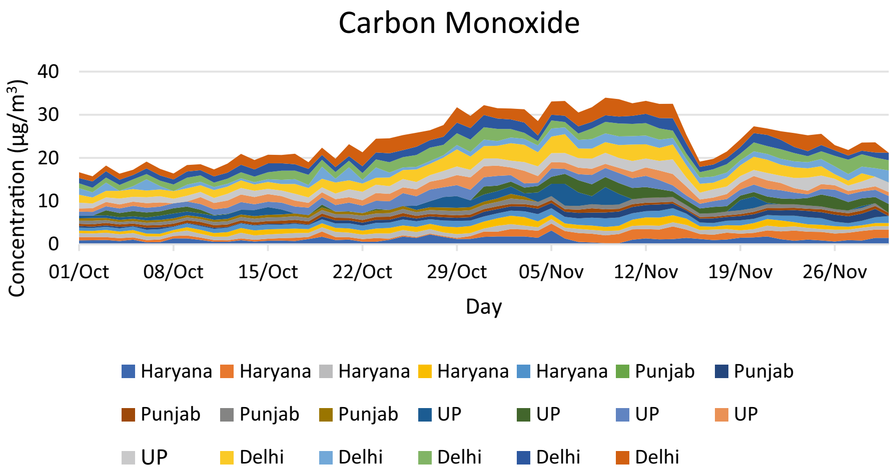


Fig. 12 Concentration levels of CO from 2016 to 2020 in IGP

during stubble burning in Punjab have also been reported by various researchers (Mittal et al., 2009; Chawala & Sandhu, 2020).

Carbon-monoxide (CO), a by-product of incomplete combustion, also shows the similar trend in their concentrations, large scale burning of stubble causes an increase in CO levels which affects all the four regions of Punjab, Haryana, Delhi, and western Uttar Pradesh (Fig. 12).

Ozone is a secondary pollutant which has a significant impact on the environment due to biomass burning (Fig. 13). Although ozone is generated during the daytime by NOx, CO and VOCs in the presence of sunlight, specifically in UV spectrum, biomass burning does not show any direct impact on Ozone but indirectly, biomass burning impacts the ozone levels. Alvarez-Mendoza et al. (2019) applied an empirical land use regression (LUR) model to understand the spatial concentration of surface ozone in Quito using Landsat-8 satellite images, air pollution measurements and meteorological variables with a better spatial resolution.

The study of these air pollutants holds significance due to the fact that the concentrations of these air pollutants remain within the permissible limit during post-monsoon season prior to initiation of paddy residue burning. However, once the stubble burning starts, the air quality degrades abruptly during these two months of October and November.

Role of wind

For dispersal of any pollutant, wind plays a major role in its dilution and dispersal. Therefore, the forward and backward trajectory of winds during October

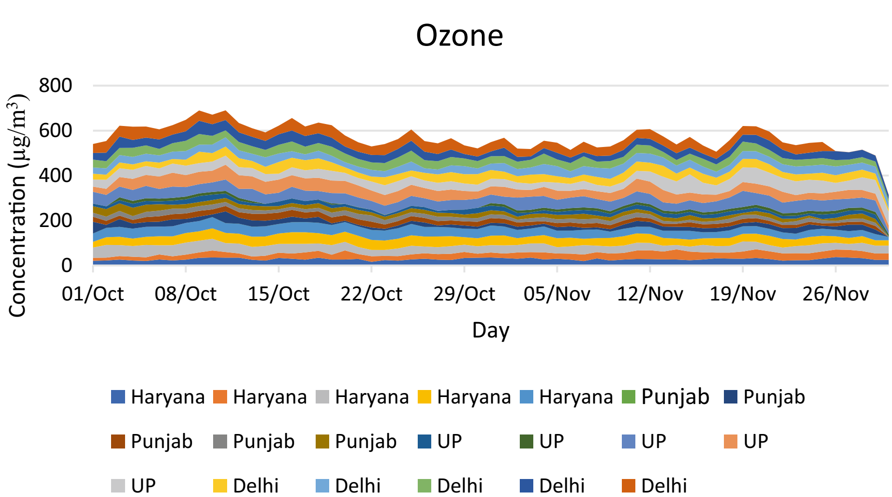
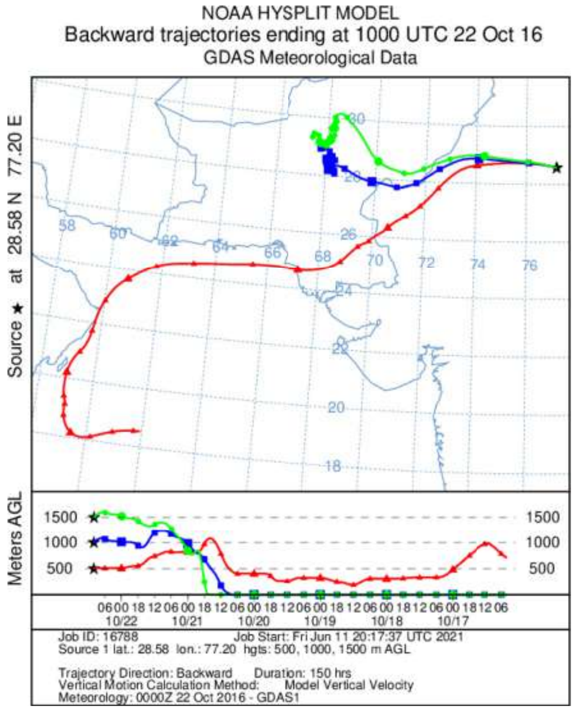
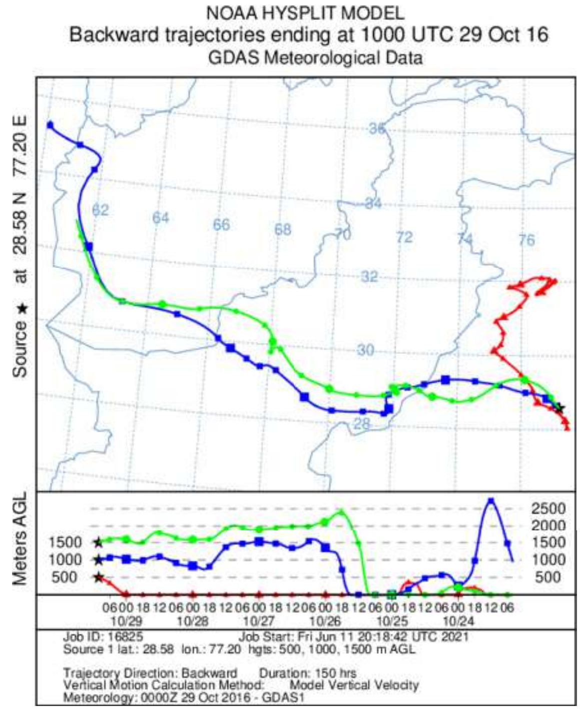


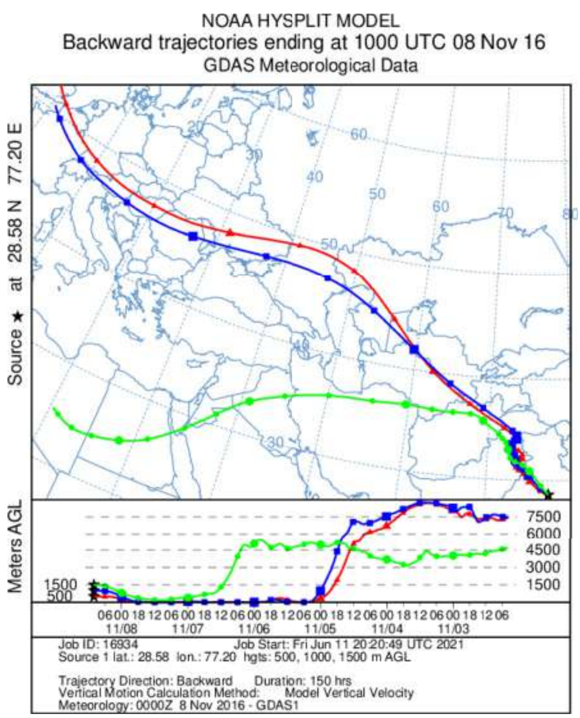
Fig. 13 Concentration levels of ozone from 2016 to 2020 in IGP



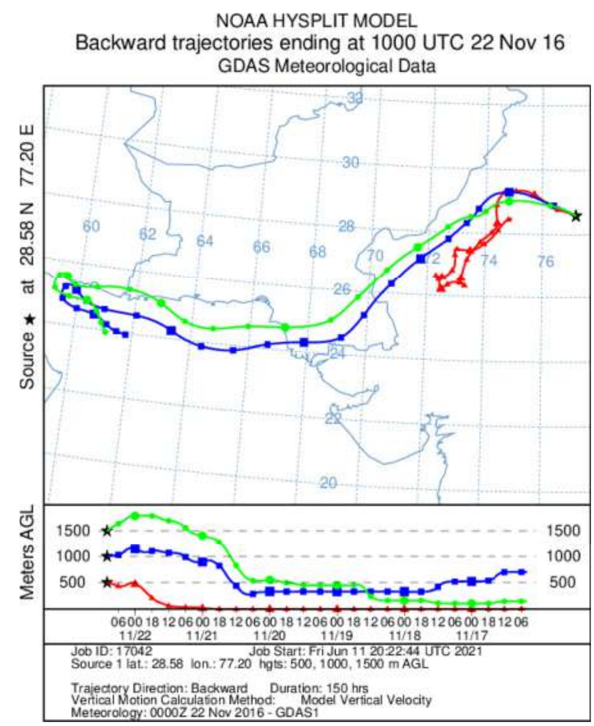
(a) Wind Trajectory on 22nd October, 2016



(b) Wind Trajectory on 29th October, 2016

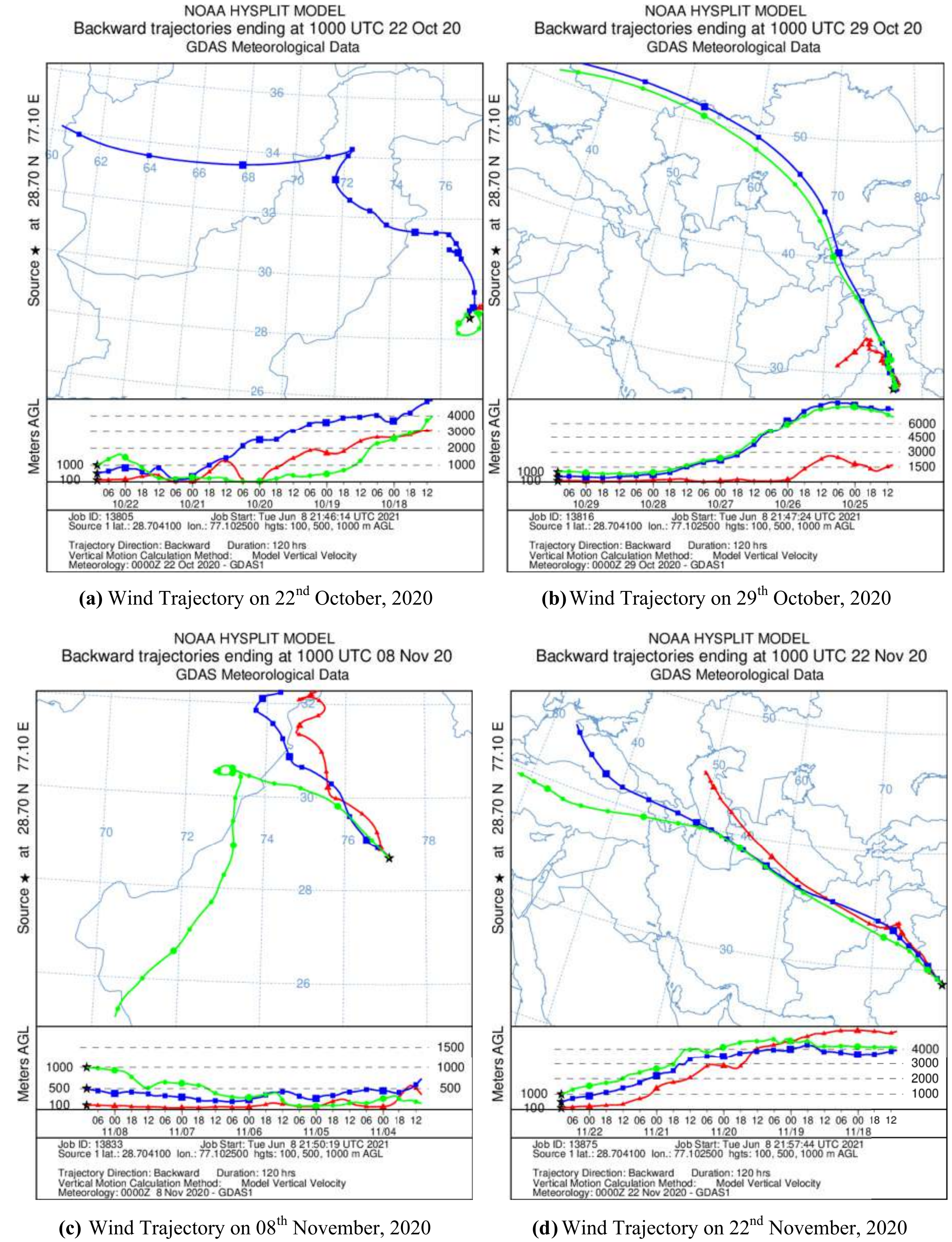


(c) Wind Trajectory on 08th November, 2016



(d) Wind Trajectory on 22nd November, 2016

Fig. 14 (**a**)–(**d**): Wind trajectory using HYSPLIT model plot for 2016



(a) Wind Trajectory on 22nd October, 2020

(b) Wind Trajectory on 29th October, 2020

(c) Wind Trajectory on 08th November, 2020

(d) Wind Trajectory on 22nd November, 2020

Fig. 15 (**a**)–(**d**): Wind trajectory using HYSPLIT model plot for 2020 and November months of 2016 and 2020 was plotted using HYSPLIT model available from NOAA Air Laboratory. The Backward wind trajectory was traced during these two months for five years from 2016 to 2020 (Figs. 14 and 15). As per the path traced at the height of 100 m, 500 m, and 1000 m, it has been observed that during the major duration of study period, the wind travelling to Delhi comes from North-Western Direction. At almost all the mentioned heights, these winds travel through Punjab, Haryana and Western UP before entering into the Delhi-NCR region. This is one of the primary reasons why Delhi becomes a smog chamber during peak stubble during period of October and November. Due to lower temperatures, onset of winter season and calmer winds in the month of October and November, these stacks of plume released by stubble burning rise slowly towards upward direction in the air. By backward wind trajectory, it can be seen that these winds continuously remain at the height of 100–500 m as shown in the Fig. 14a to d for 2016 and Fig. 15a to d during 2020.

Figure 14a to d shows the weekly wind trajectories from 22 October, 2016, to 22 November, 2016, at an altitude of 100 m, 500 m, and 1000 m. The trajectory confirms that the plume emitted by rice straw burning travel to Delhi-NCR region and engulfs Delhi in heavy pollution and smoke lowering the visibility every year during stubble burning season. Stubble burning event happen at the ground level and the behaviour of northwest wind and low temperature causes the plume boundary at lower height after which majority of stacks of plume emitted do not travel above the height of 100–500 m. This lies in human vicinity and causes the pollutants to rise in this region. Similarly, Fig. 15a to d shows the backward trajectory for the months October–November for the year 2020.

Further, every winter in the month of October and December, the National Capital Region (NCR) of Delhi faces severe degradation in air quality, which has health implications for the residents of Delhi-NCR. As a result, the wind trajectories have been plotted over the area of Punjab, Haryana and Western UP which reveal the trajectory of winds to Delhi-NCR region during study period. These wind trajectories shown in Figs. 16, 17, 18, 19, and 20 for the years 2016, 2017, 2018, 2019, and 2020, further confirming the role of wind as a carrier of air pollutants towards Delhi, and thus elevating the pollution levels

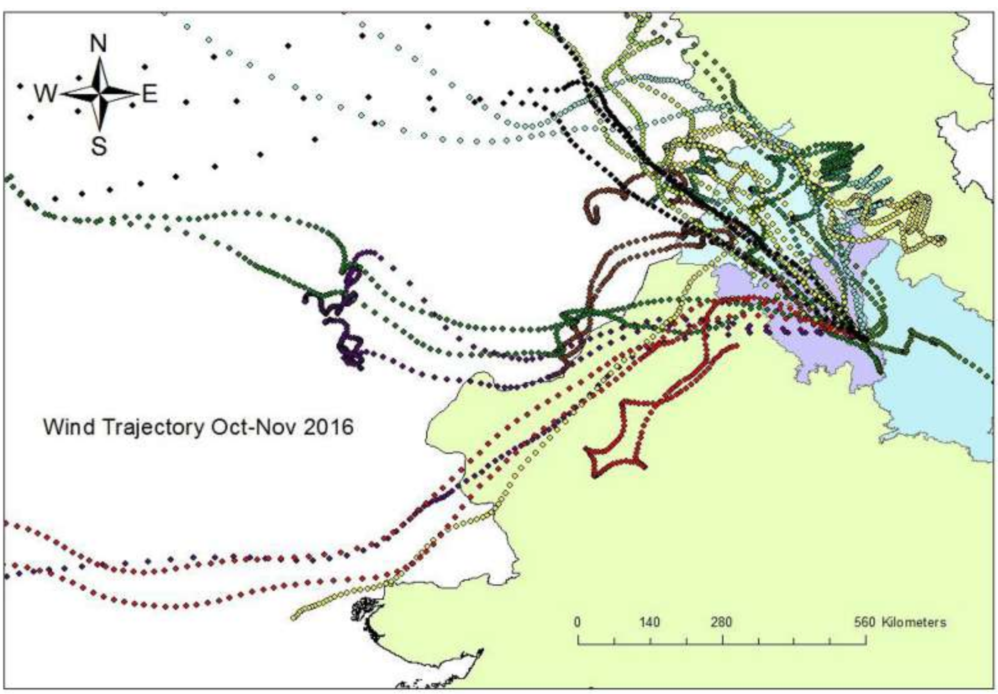


Fig. 16 Backward winds trajectory over Delhi 2016

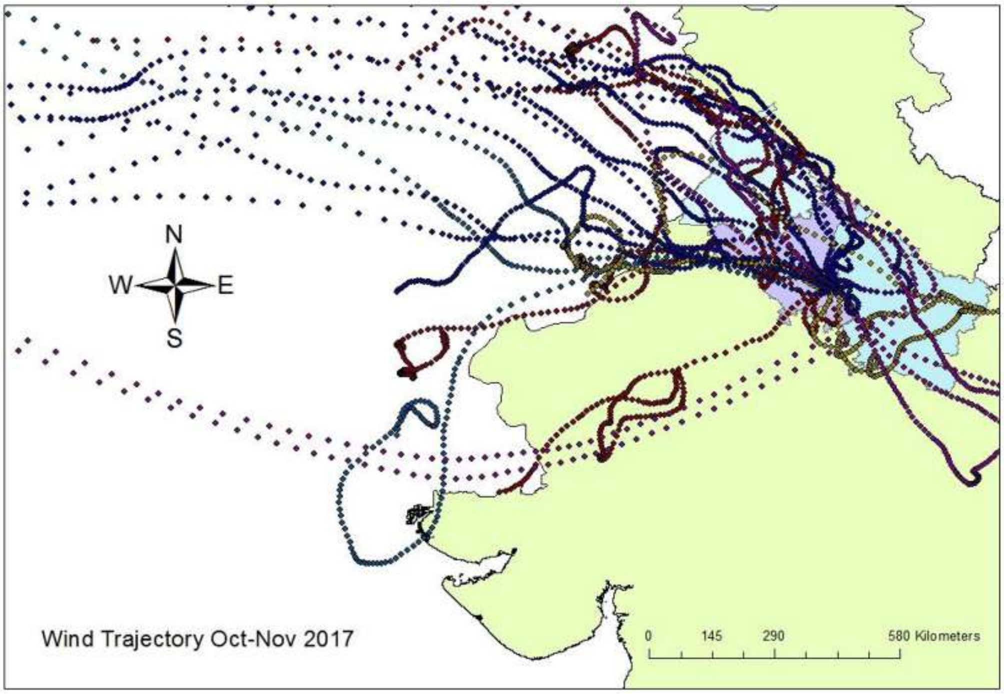


Fig. 17 Backward winds trajectory over Delhi 2017

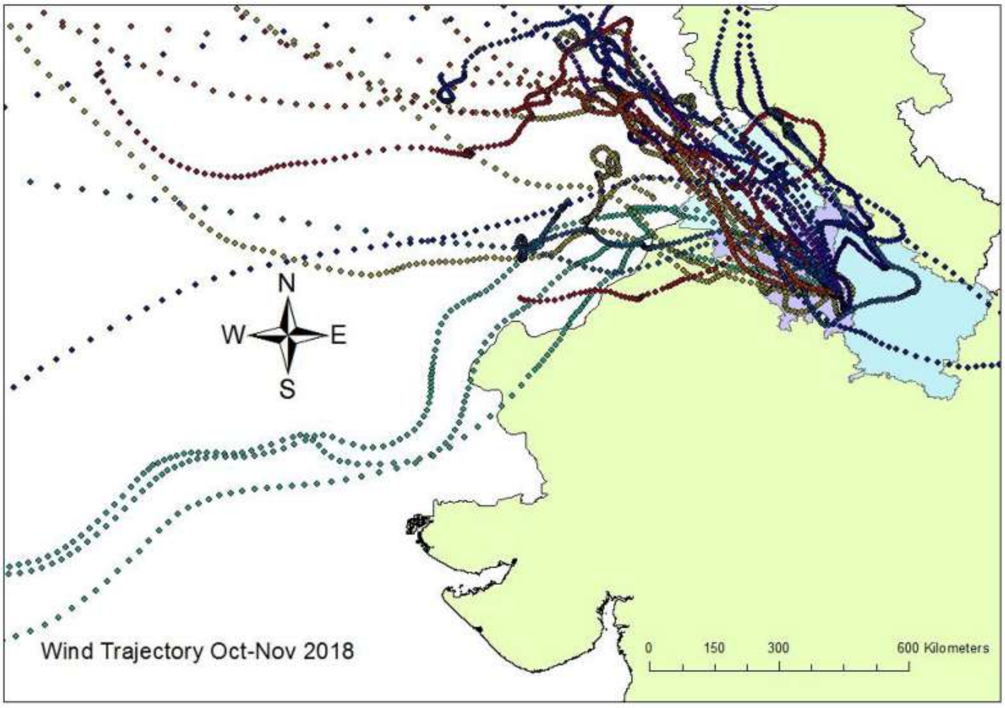


Fig. 18 Backward winds trajectory over Delhi 2018

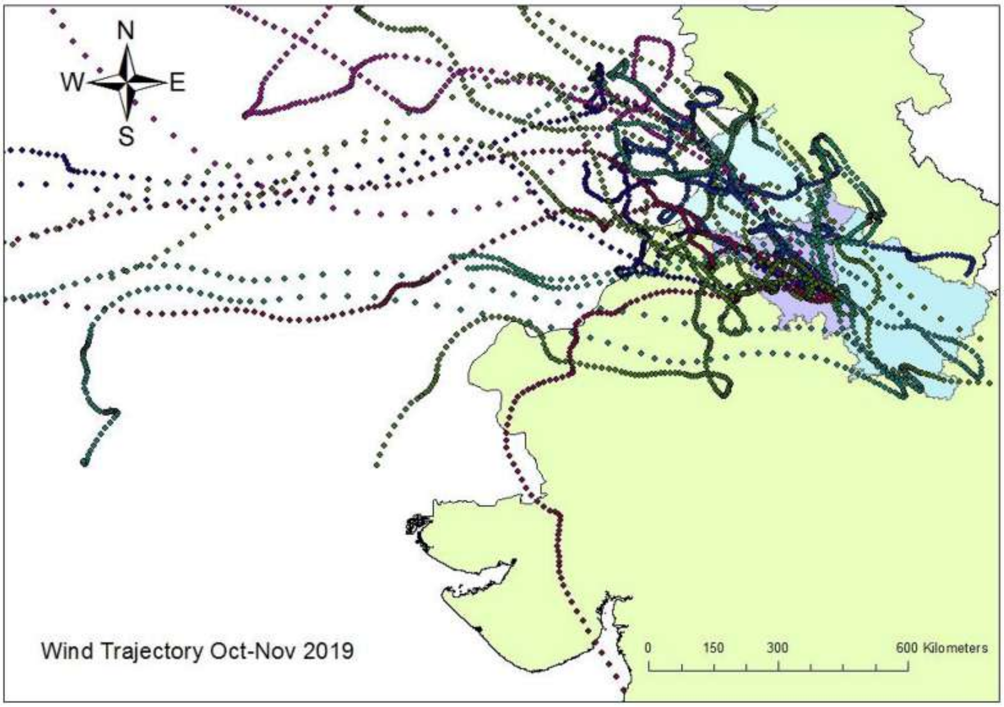


Fig. 19 Backward winds trajectory over Delhi 2019

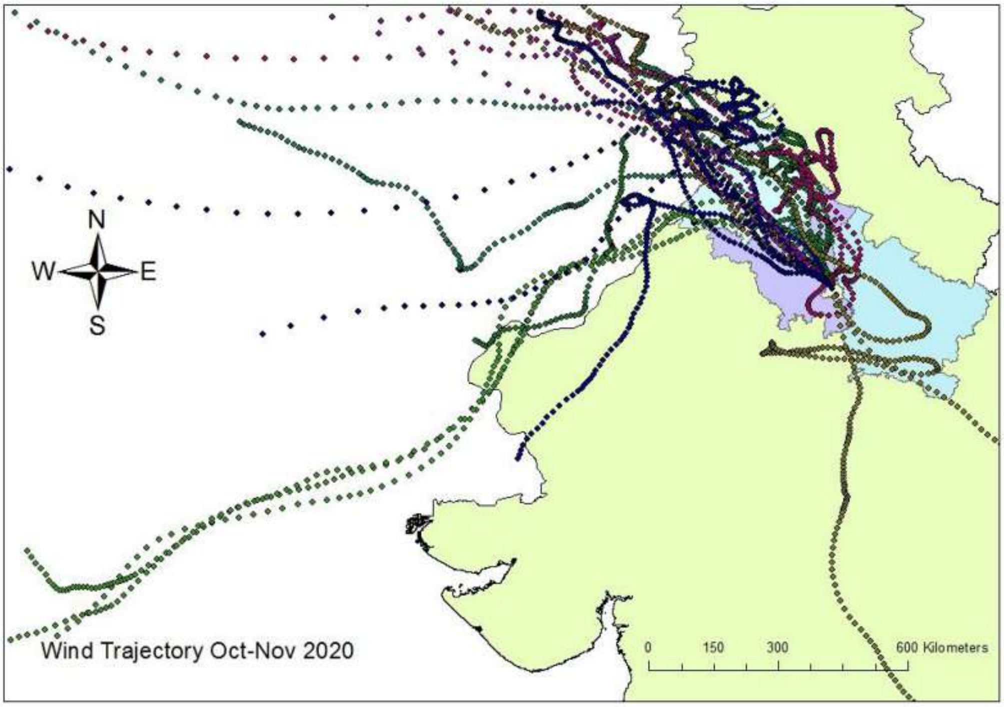


Fig. 20 Backward winds trajectory over Delhi 2020

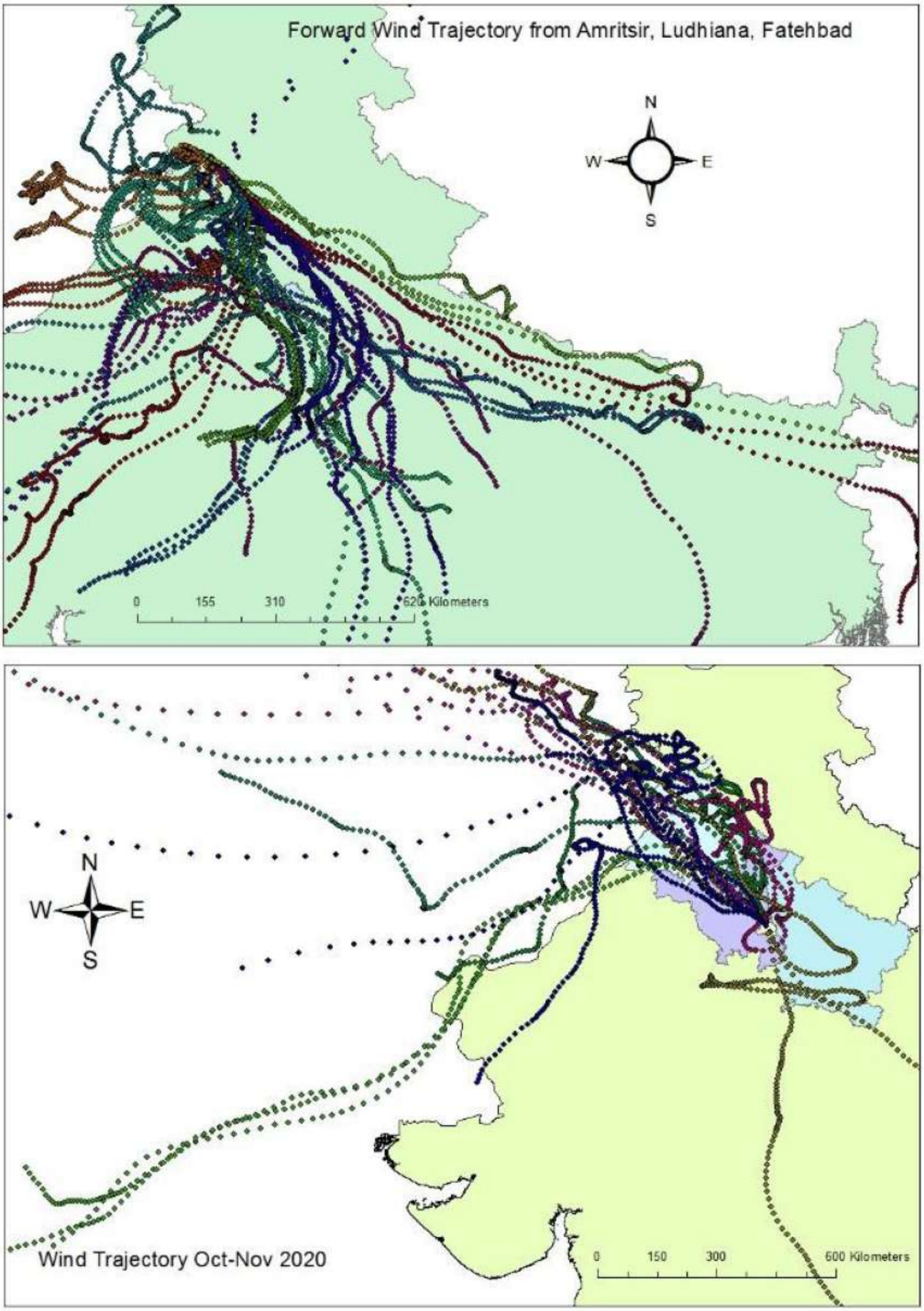


Fig. 21 Forward wind trajectory from Punjab and Haryana

in Delhi and causing an increase in respiratory problems in residents of Delhi.

If we compare the backward (Fig. 20) and the forward wind trajectory (Fig. 21) for the year 2020 over Delhi-NCR for the study period, it is observed that for wind emerging from Punjab (Ludhiana & Amritsar), Haryana (Fatehabad) over the height of 100 m, 500 m, and 1000 m (as fire plume produce low lying aerosol), their movement favors the shift of aerosol load over Delhi-NCR as shown in figure and thereby disturbing the ambient air quality of Delhi.

Summary

In the present study, an attempt was made to study the issue of stubble burning; which is a matter of serious concern in north-western India, extending from the state of Punjab, Haryana up to western parts of the state of Uttar Pradesh. This also has implications for the air quality of the National Capital Region of Delhi. Thus, this entire region of Indo-Gangetic Plains (IGP) becomes engulfed in smoke plume during the stubble burning months of October and November. The results of the present provided useful information to improve our understanding of the contribution of stubble burning emissions to air pollution. Every year, during the months of October to December, there is an observable rise in the aerosol load over Delhi region and also the concentration of pollutant levels over Delhi-NCR region increases. The analysis of meteorological parameters like wind trajectory have shown the robust validation towards the prevailing smog-like condition in Delhi-NCR during these two months.

From these results, we may conclude that after a biomass burning event in an adjoining area of Delhi, there is a change in ambient air quality of Delhi-NCR region due to increase in the particulate matter concentration (PM_{10} & $PM_{2.5}$) besides gaseous pollutants. The concentrations of $PM_{2.5}$ and PM_{10} remain highest during peak burning season from 15th October to 15th of November every year, for all the 5 years. Also, the wind trajectories over Punjab and Haryana at the height of 100 m, 500 m, and 1000 m reveal that the majority of their transport path is along the Indo-Gangetic Plains. These winds reflect the slow moment of aerosol load along this path.

Based on the results obtained from the present study, it would not be wrong to conclude that the effect of agricultural residue (stubble) burning on air quality of Delhi might be up to significant levels. Delhi has its own other sources of emissions like industrial emissions and vehicular exhausts, which also exacerbates the issue; but during the stubble burning period, the increases in pollutant level after monsoon season rises and its effect is worsened due to stagnation and inversion layer formation. The local meteorology hinders the dispersion of pollutants leading to alarming and continuous accumulation of pollutants over the whole area.

The findings of this study might be used to expand our understandings on the atmospheric processes that occur over northern India during the post-monsoon season. The pollutant, smoke plume features, and impacted regions of biomass-burning aerosols in the IGP region are critical for weather and climate research, especially given the rising trend in agricultural burning over the previous two decades. The current study's findings would help in determining the relative contribution of various internal and external sources during the agricultural residue burning season, as well as in developing comprehensive air quality improvement plans to curb the risks due to stubble burning.

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Data availability The manuscript has no associated data in other repositories. Further, all data generated or analysed during this study are included in this manuscript itself.

Declarations

Competing interests The authors declare no competing interests.

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