Research Article

Comparison of ambient air pollution levels of Amritsar during foggy conditions with that of five major north Indian cities: multivariate analysis and air mass back trajectories

Rekha Yadav[1] · Manpreet S. Bhatti[1] · Sushil K. Kansal[2] · Laxmi Das[1] · Vishakha Gilhotra[1] · Aditi Sugha[1] · Dipti Hingmire[3] · Shweta Yadav[4] · Ankit Tandon[5] · Rajbir Bhatti[6] · Anubha Goel[7] · Tuhin K. Mandal[8]

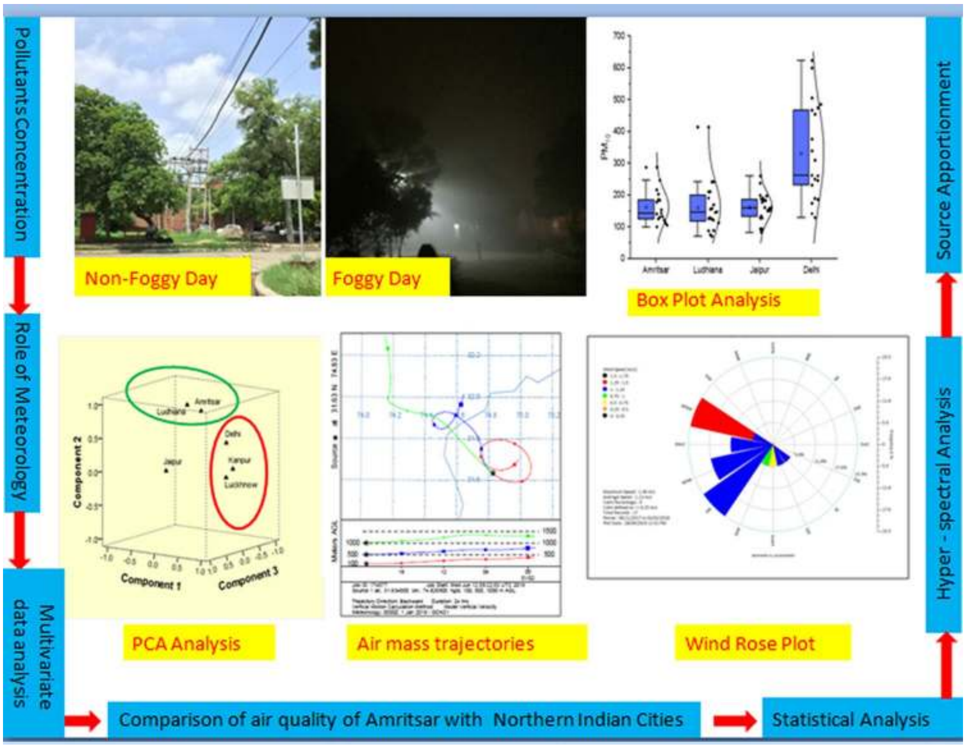
Received: 19 May 2020 / Accepted: 22 September 2020 / Published online: 3 October 2020

Abstract
In the present study, winter fog events (Nov. 2017–Feb. 2018) in Amritsar city were compared with other major cities of North India. Multivariate data analysis, along with air mass trajectory analysis, was used to explain the complex behaviour of ambient air quality during winter fog. Average particulate matter (PM) during fog events was $PM_{2.5}$ (77 µg m^{-3}), PM_{10} (162 µg m^{-3}) above the 24 h average National Ambient Air Quality Standards (NAAQS) of $PM_{2.5}$ (60 µg m^{-3}) and PM_{10} (100 µg m^{-3}), respectively prescribed by Government of India. Wind speed and visibility during fog events were studied along with prevailing wind direction for major PM episodes. Amritsar's $PM_{2.5}$ comparison with Ludhiana, Delhi, Kanpur, Lucknow, and Jaipur showed a clear link between Amritsar with Ludhiana (r = 0.807), a North Indian industrial hub. Lucknow and Kanpur had a strong correlation (r = 0.826) due to their proximity. Box-plot of $PM_{2.5}$ to PM_{10} ratio revealed a lower contribution of $PM_{2.5}$ in Amritsar as compared to other cities. Dimensionality reduction using factor analysis of ambient air quality and meteorological parameters grouped the data in order of their variance explained. The first principal component (PC-1) was $PM_{2.5}$ and PM_{10}, followed by an antagonist correlation of humidity with wind velocity and visibility in Amritsar city. Factor analysis of ambient air quality of six cities, grouped Delhi, Kanpur, and Lucknow into PC-1, followed by Ludhiana and Amritsar as PC-2 which could be due to their proximity signifying the similar ambient air quality of the sites. In order to determine the origin of air mass, 24 h backward trajectories were studied and corroborated with wind rose profile. The results revealed the transport of air masses from the west to the source location.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s42452-020-03569-2) contains supplementary material, which is available to authorized users.

✉ Manpreet S. Bhatti, mbhatti.dobes@gndu.ac.in; mbhatti73@gmail.com; Rekha Yadav, rekha1994.gndu@gmail.com; Sushil K. Kansal, sushilkk1@yahoo.co.in; Laxmi Das, kdaslaxmi@gmail.com; Vishakha Gilhotra, vishgilhotra@gmail.com; Aditi Sugha, asugha12@gmail.com; Dipti Hingmire, diptikalyanshetti@gmail.com; Shweta Yadav, shwetayadav.jnu@gmail.com; Ankit Tandon, ankittandon.cuhp@gmail.com; Rajbir Bhatti, rbhatti75@gmail.com; Anubha Goel, anubha@iitk.ac.in; Tuhin K. Mandal, tuhinkumarmandal@gmail.com | [1]Department of Botanical and Environmental Sciences, Guru Nanak Dev University, Amritsar, Punjab 143005, India. [2]Dr. SSB University Institute of Chemical Engineering and Technology, Panjab University, Chandigarh, India. [3]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, Maharashtra, India. [4]Department of Environmental Sciences, Central University of Jammu, Jammu, India. [5]Department of Environmental Sciences, Central University of Himachal Pradesh, Dharamshala, Himachal Pradesh, India. [6]Department of Pharmaceutical Sciences, Guru Nanak Dev University, Amritsar, Punjab, India. [7]Department of Civil Engineering, Indian Institute of Technology, Kanpur, India. [8]Environmental Sciences and Biomedical Metrology Division, CSIR-National Physical Laboratory, New Delhi, India.

Graphic abstract



Keywords Urban air quality · $PM_{2.5}/PM_{10}$ ratio · Moving averages · Cluster analysis · Wind rose · HYSPLIT modelling

1 Introduction

Air pollution is currently the most significant environmental threat to human health and one of the fastest-growing issues on the global health agenda. On a global scale, India is prominently visible to have an average annual population-weighted $PM_{2.5}$ concentration between 75 and 101 μg m^{-3} as per GBD [8] (Fig. S1). According to the report, the maximum annual population-weighted $PM_{2.5}$ was 99 μg m^{-3} in the year 2012 and then continually hovering above 90 μg m^{-3} as shown in Fig. 1. Neighbouring countries like Bangladesh, Pakistan, and China have annual population-weighted $PM_{2.5}$ ranging between 60 and 70 μg m^{-3} but showing improved air quality after 2013, and the global average annual population-weighted $PM_{2.5}$ is 45 μg m^{-3} (Fig. 1). Thus, air quality is a serious health concern and needs to be attended. As per the Environment Performance Index (EPI) [7] report, India ranked 178 out of 180 countries in air quality with an EPI score of 5.75. Particulate matter ($PM_{2.5}$) (aerodynamic diameter < 2.5 microns) is of most significant concern because the particles can penetrate deep into human lungs and thereby enter the bloodstream. Bell and Davis [3] studied 1952 London smog disaster and also compared with Delhi and observed total suspended solids (TSP) load of 410 μg m^{-3} for Delhi during early 1990. TSP (particle size < 45 microns) was used at those times and PM_{10} to TSP ratio was estimated at 0.6. Thus, PM_{10} was in the range of 240 μg m^{-3}. Now, better instruments and finer particles ($PM_{2.5}$) along with $PM_{2.5}$ to PM_{10} ratio are used for source apportionment. Cocktail of pollutants contributed to $PM_{2.5}$ levels in different geographical locations. The death rate in India is on the higher side (~ 110 deaths per 100,000 people) attributed to outdoor $PM_{2.5}$ exposure as compared to other neighbouring countries having similar $PM_{2.5}$ concentration [20]. $PM_{2.5}$ concentrations have a positive association with the political globalization and democracy of the nation with higher emissions and negative with lower emissions, and the study also revealed the above two factors for degrading the quality of environment [32]. The study reported $PM_{2.5}$ in the highest quartile for the countries including India, China, Korea and Italy among all G-20 nations. The definition of fog as per NOAA [23] is horizontal visibility due to tiny water droplets present in the atmosphere to

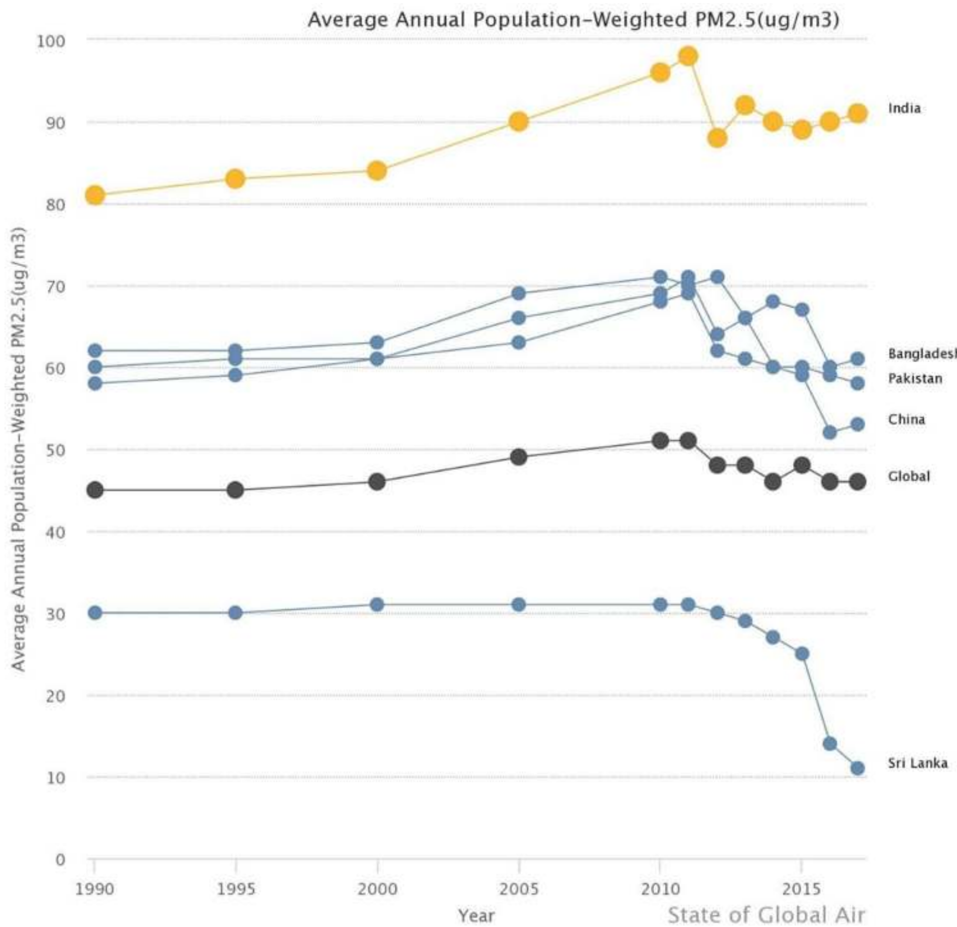


Fig. 1 Average annual population-weighted $PM_{2.5}$ ($\mu g\ m^{-3}$) of India, Bangladesh, Pakistan, China and Sri Lanka with global averages from 1990 to 2017 as per [8]

less than 1 km (< 5/8 statute mile) causing obscurations. In another paper, Quan et al. [26] reported the ideal fog when the visibility ≤ 2 km and relative humidity reported the ideal fog when the visibility ≤ 2 km and relative humidity ≥ 95%. Due to various names and categories of fog, its definition and classification remain unclear [11].

According to a report on road accidents 2017, out of the total road accidents in India, weather conditions such as fog and mists contributed to 26,982 accidents and leaving 11,090 persons dead with more than 24,000 injured [29]. Chen et al. [6] observed that an increase in the $PM_{2.5}$ concentration levels has a strong association with impaired visibility and increased vehicular density further add to poor air quality. Due to temperature inversion and urbanization, the severity of dense fog/smog is increasing year by year. The formation of fog forms over the Indo-Gangetic Plains (IGP) of the Indian region during winter months is responsible for several health hazards and economic loss [30]. In a recent report, it was found that the IGP cities were highly loaded with particulate pollution as compared to that of other cities of the country and $PM_{2.5}$ was higher during post-monsoon than the pre-monsoon [24]. In contrast, a 29 years fog study revealed increased urbanization of cities declined the occurrence of fog events over the Shanghai region as reported by Gu et al. [9]. In another study, meteorological conditions showed more significant effects in winter as compared to that of other seasons, and anthropogenic emission sources contributed to 70% in the PM_{10} dynamics [16]. Air pollution is one of the three factors that influence fog trends along with global climate change and urban heat island [9]. Among the three, urban heat island and air pollution are closely related to urban expansion. PM concentrations increase in winter months due to low Planet Boundary Layer (PBL), because of which, dispersion is affected, and the pollutants remain at ground level affecting visibility thereby becoming a barrier in transportation and also deteriorating the human health. Source apportionment of $PM_{2.5}$ and its constituents during the winter fog experiment during winter months in the capital city Delhi and the study reported the limited thickness of the PBL (307 ± 325 m) and calm winds as the primary factor maximizing $PM_{2.5}$ pollution in the winter months [1]. Meteorological parameters such as wind direction, wind velocity and transport pathways of air masses play a very crucial role in the dispersion of pollutants over an area [18, 35].

The purpose of the present study is to evaluate the air quality of Amritsar, a historical city and comparing with other major cities of north India during winter fog events using statistical data processing viz. multiple correlation, factor analysis, cluster analysis and air trajectory modelling. Further, the current examination was also directed to discover the convoluted connection between urban air qualities and fog/smog occasions during winter months. The study site is a historical city because of the Golden Temple (sacred place for Sikh pilgrimage) with more than ten thousand footfalls per day. Endeavours are being undertaken to connect fog/smog events with particulate matter in the city of Amritsar, as the city has an international air terminal and celebrated tourist spots such as Jallianwala Bagh and Wagah border to enter Pakistan. During fog events, the analysis will provide insights into the $PM_{2.5}$ to PM_{10} ratio, the correlation between air mass trajectories and wind profile.

2 Materials and methods

Air quality data was retrieved from CPCB, New Delhi for Amritsar, and neighbouring cities during fog episodes (n = 21, between Nov. 2017 and Feb. 2018) as given in Table S1. The relationship between air quality with visibility, wind velocity, and wind direction was studied systematically. Box-plot of the pollutants is analyzed to check the data variance and inter-comparison between cities. The 3-days moving averages is best suited to smoothen the curve using small data points.

2.1 Study locations and sources of data acquisition

Ambient air quality data was taken from the Central Pollution Control Board (CPCB), a statutory organization under the Ministry of Environment, Forest and Climate Change, New Delhi (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data) for Amritsar, Ludhiana, Delhi, Kanpur, Lucknow, and Jaipur for the multicity comparison. Meteorological parameters for the chosen dates of the fog events were acquired from an online meteorological site (https://www.wunderground.com). Central Control Room for Air Quality, showing about 190 continuous ambient air quality monitoring stations (CAAQMS) available online for data fetching (Fig. S2). The lowest temperature in Amritsar occurs from December to January. The western disturbances affect the weather during the winter season that is responsible for widespread rain and gusty winds along with the role of temperature inversion in building up pollution load. Both road distances as well as aerial distance are taken into consideration between the study sites. The crow flight distance (written in brackets) is also checked for the same. Ludhiana is closest to Amritsar and situated about 140 km (120 km) from Amritsar. Delhi, the capital city, is 450 km (401 km) on the southeast side. Historical city Jaipur in Rajasthan state is at a distance of 670 km (532 km) from Amritsar. Lucknow and Kanpur, major cities of Uttar Pradesh state are farthest from Amritsar (Fig. S3).

2.2 Air pollution in major cities of north India

2.2.1 Multiple correlation analysis

Multiple correlation analysis is the statistical tool used to study the interrelationships between the different variables and the correlation coefficient (r) ranged between − 1 to + 1. The significance of the correlation coefficient is a function of data points (n) or degree of freedom (DoF). Subsequently, the p value is obtained ($p < 0.05$ is significant and $p < 0.001$ is highly-significant). Correlation indicates the degree of association of $PM_{2.5}$ with other north India cities. Pearson correlation coefficient (most commonly used in continuous data) has been used in the present study.

2.2.2 Multivariate data analysis

2.2.2.1 Factor analysis Factor analysis is a method of reformulating a set of observed variables into a set of new independent variables known as factors. This statistical method identifies the group of elements whose concentration fluctuates together from one sample to another and does the separation of these elements into factors. Statistical software (SPSS v16) was used for Principal Component Analysis (PCA) with varimax rotation, a term called factor analysis, which aligns the multidimensionality reduction by aligning data in two/three Principal Component (PC) axes. Another criterion for limiting the number of PC is eigenvalues (> 1 is considered statistically significant). The rotated component matrix (3-D plots) classifies various components based on the correlation matrix of the datasheet.

2.2.2.2 Cluster analysis Cluster analysis is a multivariate analysis statistical tool used for clustering or grouping the variables based on Euclidean distances and the similarities. The small or low Euclidean distance indicates the close association between the variables, whereas the more considerable distances indicate the dissimilarities. The variables with the highest similarities are linked first and then the others accordingly. In this, we used hierarchical cluster methods using statistical OriginPro v9 software. Both factor analysis and cluster analysis was applied to the following case studies:

Case 1 Relationship among meteorological parameters and air pollutants of Amritsar city.

Case 2 Association of $PM_{2.5}$ of Amritsar with other northern cities was studied.

2.3 Air mass trajectory

Air mass trajectories are used to study the pathway of air masses in the environment by different researchers [4, 12, 14, 28, 31] and to identify the sources of pollutants. Backward trajectories of 24 h were generated at the height of (100, 500, 1000) m above ground level (AGL) using Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) model provided by National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) of the United States Department of Commerce. Global Data Assimilation System (GDAS) computation was used for vertical velocity profiling & briefly describes the procedure for the plotting of air mass trajectories (Fig. S4). Air mass trajectories were computed for maximum PM_{10} and $PM_{2.5}$ loadings.

3 Results and discussion

3.1 Air quality of Amritsar city

Average PM during fog events between Nov. 2017 to Feb. 2018 was 77 μg m^{-3} ($PM_{2.5}$) and 162 μg m^{-3} (PM_{10}) as given Table S1. The air quality data of various pollutants were scaled using the logarithm of pollutant concentration on the Y-axis to study a wide range of data on a shorter scale. PM_{10} and $PM_{2.5}$ were found to be the prominent pollutant in Amritsar (Fig. S5). Ambient air quality parameters were compared with National Ambient Air Quality Standards (NAAQS) set by the Central Pollution Control Board, New Delhi [5]. The ratio between the mean of particular pollutants to the NAAQS was compared. It was found that the values for NO_2, SO_2, O_3, were found to be 0.5, 0.04, 0.18, which is less than 1 indicated the pollutant concentration is less than the national ambient air quality standards. Whereas, the ratio of PM_{10} and $PM_{2.5}$ were found to be 1.62 and 1.28 respectively, indicating higher concentration than national ambient air quality standards. In previously reported studies of Amritsar, the average PM_{10} and $PM_{2.5}$ concentration was 160 μg m^{-3} from June to December 2012 [10] and 147.6 μg m^{-3} for a 3 months study from December 2011 to February 2012 [19] respectively.

PM_{10} was measured at six different sites in Amritsar city and the study reported that PM_{10} ranged between 159 and 215 μg m^{-3} [17]. Whereas, Ravindra et al. [28] reported $PM_{2.5}$ (178 ± 84 μg m^{-3}) and PM_{10} (252 ± 108 μg m^{-3}) during 7-days of continuous sampling using beta ray attenuation method from 9 to 15 November 2016. Due to different seasons and meteorological conditions, there is no clear trend in the PM load. In the present study, the average $PM_{2.5}$ (77 μg m^{-3}) and PM_{10} (162 μg m^{-3}) were obtained for specific fog events. The 24 h average observed concentrations of PM_{10} and $PM_{2.5}$ exceeded the NAAQS of 100 μg m^{-3} for PM_{10} and 60 μg m^{-3} for $PM_{2.5}$, whereas the other pollutants were within the permissible range. In the winter season due to the occurrence of the foggy conditions, the temperature inversion occurs close to the earth's surface which as a result does not allow the dispersion of pollutants. Due to this, pollutants get trapped in a smaller volume of the atmosphere close to the earth, thereby increased concentrations.

The temperature ranged between 9.1 and 20.7 °C during the sampling period. As a result of inversion and stagnant conditions with average wind speed was 1.13 m s^{-1}, there is little dispersion of pollutants. The air quality further deteriorates due to the burning of rice straw in a very narrow window of around 30 days starting from mid-October to November in Amritsar. The prominent source of this high concentration of $PM_{2.5}$ in the western IGP is attributed due to stubble burning in the area [24]. Another study also reported that the high PM loading in Delhi (January 2013 to December 2016) was prominently due to biomass burning and residential heating in Punjab and Haryana in the winter season [15]. During the burning of rice and wheat crop residues, the concentration of PM_{10} increases by 66% and 51% when compared to other months, except for the burning time of crop residue [2].

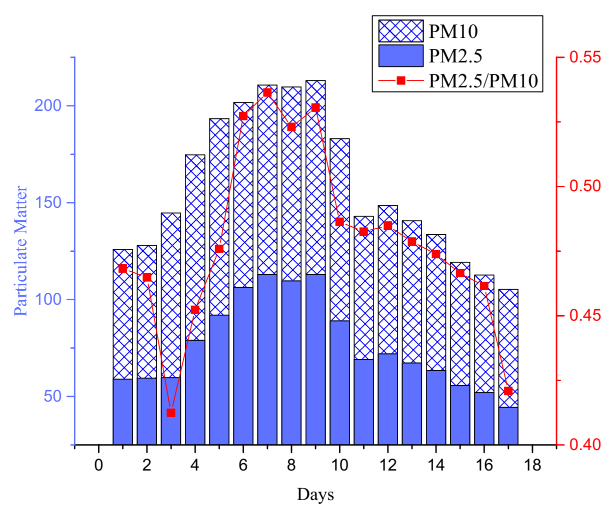


Fig. 2 Contribution of $PM_{2.5}$ in PM_{10} along with $PM_{2.5}/PM_{10}$ ratio using 3-day moving averages during fog in Amritsar city [particulate matter in (μg m^{-3})]

3.2 Moving averages

The 3-day moving average was applied on PM_{10}, $PM_{2.5}$, and $PM_{2.5}/PM_{10}$ ratio to smoothen the data by filtering out the noise from the collected data set. There is an increase in $PM_{2.5}/PM_{10}$ ratio up from 0.45 ± 0.02 (Nov 2017) to 0.52 ± 0.02 (Dec 2017) and hovering around 0.52 and then started decreasing with an average ratio of 0.47 (Fig. 2). This states that $PM_{2.5}$ contributes 47% of PM_{10}. In the previous study, $PM_{2.5}/PM_{10}$ ratio was 0.69 for Amritsar during November 2016 [28]. In the present study, the lower contribution of $PM_{2.5}$ may be due to the deposition of fine particles in the fog along with the higher relative humidity that favours the clustering of secondary aerosols precursors and as a result, agglomerations of fine particles.

3.3 Multivariate data analysis of Amritsar

3.3.1 Factor analysis

Factor analysis was applied on 10 independent variables (dew-point, humidity, wind speed, visibility, CO, NO_2, SO_2, O_3, $PM_{2.5}$ and PM_{10}) to resolve similar behaving variables into a single factor. Multidimensional scaling resolved by three PCs accounted for 76.3% of the total variance (Table S2). PC-1 explained that 45.3% variance and factors with the significant loading (> 0.7) for CO, $PM_{2.5}$, and PM_{10}. CO is the by-product of the incomplete combustion of petroleum, coal, solid waste and fuel wood which signifies incomplete combustion as the biggest contributor for high PM loading. During winter, open refuge burning and vehicular emissions were the significant contributors of CO, thereby increasing PM load in the Amritsar city. PC-2 included wind speed, visibility and humidity (negatively correlated) explaining 19.4% of the variance. PC-3 explained that 11.5% of the total variance included SO_2 and O_3 with significant factor loadings (Fig. S6). This technique resolved the importance of variables in order of their significance. The major factors such as wind velocity, wind direction, and atmospheric stability are known as primary/basic meteorological parameters since the dispersion and diffusion of pollutants depend mainly on these factors. On the other hand, factors like ambient temperature, humidity, rainfall, atmospheric pressure etc. are known as secondary meteorological parameters as these factors control the dispersion of the pollutants indirectly by affecting the primary factors [35]. Sharma and Mandal [31] conducted a 5-year study in Delhi and found NH_3, NO, NO_2 and CO under PC-1 and meteorological parameters including temperature, relative humidity and wind speed under PC-2. It has been observed that grouping of variables in a city depends upon input variables, season and type of rotation applied, which affect the grouping of variables. This grouping will be different for different seasons and during fog events, CO and PM load are the most significant variables that explain ambient air quality.

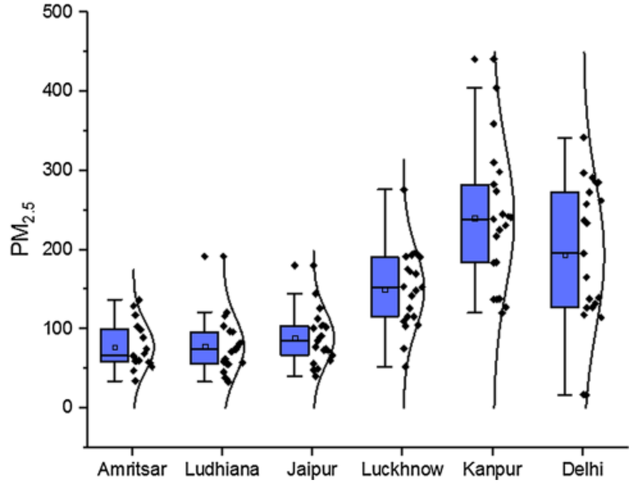


Fig. 3 Box plot of north Indian cities showing $PM_{2.5}$ (μg m^{-3})

3.3.2 Cluster analysis

$PM_{2.5}$ and PM_{10} showed maximum similarity and the minimum euclidean distance of 0.1 and may be attributed to the similar emission sources. CO, $PM_{2.5}$, PM_{10}, O_3, and SO_2 are distant from nitrogenous pollutants with a score of 1.3, whereas SO_2 is distant from all other contaminants which are released from coal-burning emissions **(**Fig. S7). Also, SO_2 concentrations are well within NAAQS having the least variance in data for Amritsar city. The maximum likelihood of ammonia along with the NO, CO, and NO_2 suggested the dominance of traffic sources in the area.

3.4 Comparison of air quality with North Indian cities

The air quality of six major cities of north India was compared during winter fog. The maximum load of $PM_{2.5}$ in the winter was found for Kanpur, Delhi followed by Lucknow. Variability of $PM_{2.5}$ was highest for Kanpur followed by Delhi (Fig. 3). PM_{10} was highest for the capital city Delhi among all locations (Fig. S8). Navinya et al. [24] reported the annual mean concentration of $PM_{2.5}$ for Amritsar and Ludhiana was found to be 50–60 μg m^{-3} whereas it was 90–100 μg m^{-3} for Lucknow and Kanpur from January 2015 to March 2018. Bisht et al. [4] investigated the annual carbonaceous aerosols from January-December 2012 for Delhi and found $PM_{2.5}$ > 200 μg m^{-3} during stubble burning episodes. The drastic increase of $PM_{2.5}$ during the post-monsoon is associated with the stubble burning episodes in north India that lead to the peak PM pollution. The above study found that the highest $PM_{2.5}$ was found from October to January. A study reported the average concentration of PM_{10} from January–February 2015 as 303.9 ± 216.6 μg m^{-3} and a maximum of 700.2 μg m^{-3} during the winter months in Delhi. The major contributing sources include re-suspension of dust and open burning activities in the area [12]. PM_{10} concentration during winter was found to be higher than summer period during 6 months seasonal study (January to June 2015) in Delhi and this was attributed to calm weather conditions and a shallow PBL [12]. Pant et al. [25] reported higher concentration of $PM_{2.5}$ in winter (276.9 ± 99.9 μg m^{-3}) as compared to summer (58.2 ± 35.0 μg m^{-3}) months at high traffic junction in Delhi between December 2013 and June 2014. The higher concentration during winter months was due to low wind speeds, higher humidity, diffused solar radiation, and the role of frequently used unregulated open burning of biomass/waste combustion as a heating source during the winter season.

The aerosols remain intact in the shallow PBL, and the hygroscopic growth promotes the formation of fog/haze conditions in the winter season. Ram and Sarin [27] studied aerosol loading in the city of Kanpur during 2007–2009, the study found higher PM_{10} concentration in winter (189 ± 64) μg m^{-3} from December to February in comparison to that of summer months of April to June (146 ± 41) μg m^{-3}. Reason for high PM load was attributed to biomass burning activities, vehicular emissions, calm atmospheric conditions and shallow PBL during winter. In another study, PBL had inversely relation with $PM_{2.5}$ concentrations and fog-haze events resulted in a 94% decline of incoming solar radiations [21]. Meng et al. [22] studied the role of meteorological parameters on the fine particle pollution in northeast China using multiple regression methods and concluded that PBL, temperature inversion and wind speed are the most critical factors that affect the deposition and dilution of $PM_{2.5}$. The higher relative humidity (RH) favours the formation of fog in the environment as it inhibits the sunlight due to which the surface heating declines, and thus shallow PBL is formed. The aerosols remain intact in shallow boundary layers and could not get dispersed as a result, and the pollution load is increased during fog episodes. Guttikunda et al. [13] studied air pollutants data for 20 Indian cities using emission inventory and chemical transport modeling. The estimated annual emission inventory for year 2015 was 8600 tons/year ($PM_{2.5}$) and 13,450 tons/year (PM_{10}) and outside boundary contribution (52.7%) to the urban airshed was highest among all cities.

Table 1 Multiple correlation analysis for particulate matter of six major cities of north India ($PM_{2.5}$ upper half and PM_{10} lower half)

	Amritsar	Ludhiana	Delhi	Jaipur	Kanpur	Luckhnow
Amritsar	1.000	**0.807**	0.583	0.249	0.395	0.273
Ludhiana	**0.876**	1.000	0.454	0.210	0.079	0.039
Delhi	0.378	0.313	1.000	0.234	0.689	**0.727**
Jaipur	0.484	0.290	0.340	1.000	0.215	0.374
Kanpur	–	–	–	–	1.000	**0.826**
Luckhnow	–	–	–	–	–	1.000

Bold terms are significant at p-value < 0.001 at 15 degree of freedom

Table 2 Comparison of results using different multivariate techniques

	Grouping of variables	Variance explained	Remarks
Factor analysis (Amritsar)			
PC-1	$PM_{2.5}$, PM_{10}, Dew-point, CO	45.3%	Association of incomplete combustion (CO) with particulate matter
PC-2	RH, Wind speed, Visibility	19.4%	RH is oppositely grouped with the other two variables
PC-3	SO_2, O_3	11.5%	
Cluster analysis (Amritsar)			
Group-1	$PM_{2.5}$ and PM_{10}	Euclidean distance 0.1	
Group-2	CO, $PM_{2.5}$, PM_{10}, O_3, SO_2	Euclidean distance 1.3	
Factor analysis of North Indian cities			
PC-1	Delhi, Kanpur, Lucknow	52.3%	More than 50% variance explained
PC-2	Amritsar, Ludhiana	24.4%	Proximity to each other
PC-3	Jaipur	14.6%	Least variance explained

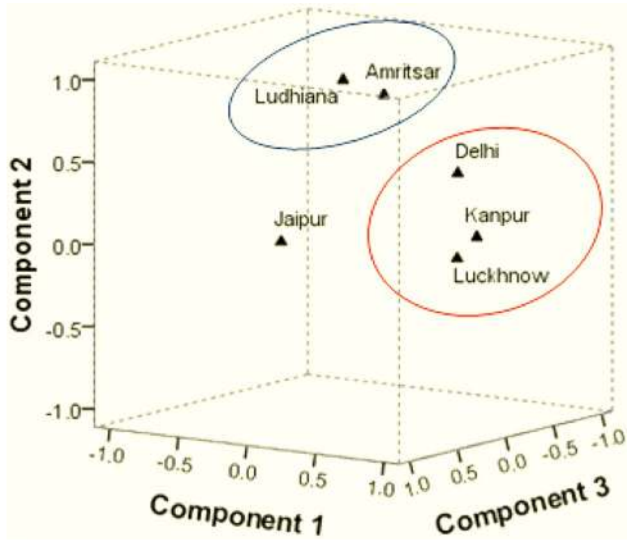


Fig. 4 3-D factor loading plot of $PM_{2.5}$ for the association between northern Indian cities

3.4.1 Multiple correlation analysis

Multiple correlation analysis is the statistical tool that is used to study the association of $PM_{2.5}$ and PM_{10} pollution among the various cities of northern India. The strong significant correlation was observed between neighbouring cities Amritsar and Ludhiana with the r = 0.807 and r = 0.876 for $PM_{2.5}$ and PM_{10} respectively at highly significant *p* value < 0.001. Similarly, a strong correlation was observed between Kanpur and Lucknow (r = 0.826), with inter-distance of ~ 90 km (Table 1). Ravindra et al. [28] also reported the significant correlation (r = 0.71–0.81) between $PM_{2.5}$ and PM_{10} for Amritsar city.

3.4.2 Factor analysis

Factor analysis was done for $PM_{2.5}$ concentration of different cities (Amritsar, Delhi, Jaipur, Kanpur, Lucknow and Ludhiana). Scree-plot and varimax rotation resolved multiple parameters into three PCs and explained 91% of the total variance (Table S3). Table 2 shows PCs and their variance along with factor loading. A 3-D view of the three components is presented in Fig. 4. Lucknow, Kanpur, and Delhi (PC-1) and Ludhiana and Amritsar (PC-2) are in a single plane indicating similar ambient air quality patterns.

3.4.3 $PM_{2.5}/PM_{10}$ ratio

The ratio analysis is used to differentiate the anthropogenic aerosols (fine mode dominant aerosols) and dust aerosols (coarse mode dominant aerosols). The ratio (> 0.6) during the winter suggests the major contribution of the fine aerosols and ratio (0.4–0.6) in summer, suggesting the dominance of coarser particles in the degraded atmospheric conditions [33]. The comparison was done only for the four north Indian cities (Amritsar, Ludhiana, Jaipur and Delhi). The data for PM_{10} was not available for Lucknow and Kanpur. The ratio was highest for Delhi (median value of 0.6), which signifies that the higher contribution of $PM_{2.5}$ as composed of finer particles followed by other cities Jaipur, Amritsar, and Ludhiana as shown in Fig. S9. Closely analyzing the data points of Delhi, two data sets are showing a very high $PM_{2.5}$ pollution load as that of other data points highlighted in red circles in Fig. S9. Median values in the increasing order of the cities are Delhi (0.57) Jaipur (0.51), Ludhiana (0.49) and Amritsar (0.47) as shown in Fig. S9. The fraction of fine particles in Delhi, the national capital city, was maximum followed by other sites and minimum for Amritsar. The maximum ratio of the study site indicates the severe particle pollution of the region [34]. $PM_{2.5}$ to PM_{10} ratio is 0.41–0.53 and implies the characteristics of particle pollution, i.e., the higher ratio implies the anthropogenic sources and lower ratio signifies the involvement of coarse particles (natural sources). Amritsar has the lowest variability, followed by Ludhiana, Jaipur, and Delhi, as shown in the probability curve as shown in Fig. S9. Awasthi et al. [2] studied the distribution of particulate pollution during crop residue burning in Patiala from December 2007 to February 2009 and found the $PM_{2.5}/PM_{10}$ ratio 0.58 and 0.61 in 2008 and 2009 respectively. The study reported that the $PM_{2.5}$ to PM_{10} ratio gets elevated in the winter months due to finer particles fraction contribution as compared to that of other seasons. The less solar heating, low planet boundary layer height in the winter season does not allow the dispersion of pollutants to the outer atmosphere due to

Table 3 Study of HYSPLIT on highly polluted days for Amritsar city

Event	Wind velocity ($km\ h^{-1}$)	Wind direction (°)	Originated from	PM_{10} ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	Visibility (m)
6 Nov. 2017	1.07	273	Lahore, Pakistan	287	129	500
25 Dec. 2017	1.04	239	Rawalpindi, Pakistan	216	117	1300
2 Jan. 2018	1.25	127	Gujranwala, Pakistan	243	137	400

which the pollutants remain confined to the ground level and as a result, the pollution load along with $PM_{2.5}$ to PM_{10} ratio in the winter season is more.

3.5 Air mass trajectory and wind rose

From literature review, we have also found that commonly used heights and duration were 1 day i.e. 24 h duration and three different heights (100, 500, 1000 m) in response to the source location were chosen for computing backward trajectories. In the present study, 24 h backward air mass trajectories were computed for selected days showing maximum particulate matter. The red colour line shows air mass trajectory at an altitude of 100 m, the blue at 500 m and green at the altitude of 1000 m AGL. The highest concentration of PM_{10} was measured as 287 μg m^{-3} on 6 Nov 2017, and this also affected the visibility (< 500 m) of the area. Backward trajectory indicated air mass origin from Gujranwala, Pakistan, which is about 100 km from Amritsar (Fig. S10). The wind rose also supported using predominant wind direction (west, 270°) with a wind speed of ~ 0.83 m s^{-1} (Fig. S11). Similarly, air masses trajectory for 500 m and 1000 m also originated from Pakistan bordering Afghanistan. Pollution load again enhanced during the New-Year celebrations on 1 Jan 2018, with low visibility (< 400 m) due to dense fog conditions in Amritsar. Fig. S12-13 shows air mass backward trajectory for 25 Dec 2017 and 2 Jan 2018 respectively with description in Table 3. A wind rose and air mass trajectories indicated trans-boundary movement from Pakistan (Table 3), which may contribute to the building-up of air pollution in Amritsar. Yearlong study in Delhi during 2012 reported low wind speed (up to 3 m s^{-1}) of and calm atmospheric conditions inhibiting the escape of pollutants and north-west pathway of trajectories to the source location [4], similar to our study. Jain et al. [14] also revealed the origin of $PM_{2.5}$ mass emissions from northwest India along with source apportionment and chemical characteristics of $PM_{2.5}$ using multivariate data analysis from Jan 2013 to Dec 2014 in Delhi. Another study of Delhi conducted from January 2011 to December 2015 reported the origin of air trajectories from north-western to the source station during the winter months [31]. The transport pathways of the air mass trajectories in the winter months of January and February 2015 in the capital city was found to be from northwest in Delhi [12] and Patiala from August 2007 to January 2010 the predominant wind direction in the winter months was found to be northwest [2]. The high loading of PM in the area was prominently due to biomass burning and residential heating in Punjab and Haryana in the winter season [15]. The prevailing wind direction for a week-long study during November 2016 in Amritsar was found to be southeast at an average wind speed of 2.81 ± 1.28 m s^{-1} [28]. A summary table for the above studies has been shown in Table S5. Authors observed that many source apportionment studies in north India predicted the role of northwest monsoons during Oct–Dec. period and then mentioned stubble burning events in Punjab and Haryana state for high PM load.

4 Conclusions

In this study, detailed description and website sources for fetching air quality data are discussed, along with a brief overview of satellite-based air mass trajectory analysis. The meteorological variables were clustered using boxplots, multiple correlations, factor analysis and cluster analysis. The prominent air pollutants in the holy city of Amritsar were $PM_{2.5}$ and PM_{10}. Comparative study of northern Indian cities showed Delhi had a maximum load of PM_{10} among the six cities, and Kanpur had a maximum load of $PM_{2.5}$. Analysis of $PM_{2.5}/PM_{10}$ ratio showed a 60% contribution in Delhi of finer particles $PM_{2.5}$ as compared to 40% in Amritsar. The analysis has inherent limitations due to limited data and sources of emission inventory. There is a need for comprehensive study related to transport sector pollution inventories, open waste burning and industrial sources to pinpoint reasons for poor air quality. Epidemiology of air quality based illness is not performed routinely in India and this should not be confused with the non-existence of health risk due to air pollution. The deployment of the ambient air quality monitoring station towards the west of Amritsar delineates the contribution from across the international border as air mass movement from the west is shown by both wind rose and trajectory plots.

Acknowledgements Authors are grateful to NOAA Air Resources Laboratory (ARL) for the provision of HYSPLIT transport, and dispersion model and READY website (http://www.ready.noaa.gov) results used in this publication. Authors acknowledge funding from UGC-RUSA support for procurement of ambient air quality sampler. Authors are thankful to three anonymous reviewers for their critical feedback.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Ali K, Acharja P, Trivedi DK, Kulkarni R, Pithani P, Safai PD, Chate DM, Ghude S, Jenamani RK, Rajeevan M (2019) Characterisation and source identification of $PM_{2.5}$ and its chemical and carbonaceous constituents during Winter Fog Experiment 2015–16

at IGI Airport, Delhi. Sci Total Environ 662:687–696. https://doi.org/10.1016/j.scitotenv.2019.01.285
2. Awasthi A, Agarwal R, Mittal SK, Singh N, Singh K, Gupta PK (2011) Study of size and mass distribution of particulate matter due to crop residue burning with seasonal variation in rural area of Punjab, India. J Environ Monit 13(4):1073–1081. https://doi.org/10.1039/c1em10019j
3. Bell ML, Davis DL (2001) Reassessment of the lethal London fog of 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. Environ Health Perspect 109(suppl 3):389–394. https://doi.org/10.1289/ehp.01109s3389
4. Bisht DS, Dumka UC, Kaskaoutis DG, Pipal AS, Srivastava AK, Soni VK, Attri SD, Sateesh M, Tiwari S (2015) Carbonaceous aerosols and pollutants over Delhi urban environment: temporal evolution, source apportionment and radiative forcing. Sci Total Environ 521:431–445. https://doi.org/10.1016/j.scitotenv.2015.03.083
5. Central Pollution Control Board (2009) National Ambient Air Quality Standards, 2009. Downloaded on 20 Oct 2019. https://cpcb.nic.in/displaypdf.php?id=aG9tZS9haXItcG9sbHV0aW9uL1JlY3ZlZC1OYXRpb25hbC5wZGY
6. Chen J, Qiu S, Shang J, Wilfrid OM, Liu X, Tian H, Boman J (2014) Impact of relative humidity and water soluble constituents of $PM_{2.5}$ on visibility impairment in Beijing, China. Aerosol Air Qual Res 14(1):260–268. https://doi.org/10.4209/aaqr.2012.12.0360
7. EPI (2018) Environment Performance Index by Yale University. Downloaded on 22 Dec 2018. https://epi.envirocenter.yale.edu/epi-country-report/IND
8. GBD (2017) Global Burden disease study. Downloaded on 18 Aug 2019. https://www.stateofglobalair.org/data/#/air/plot
9. Gu Y, Kusaka H, Doan VQ, Tan J (2019) Impacts of urban expansion on fog types in Shanghai, China: numerical experiments by WRF model. Atmos Res 220:57–74. https://doi.org/10.1016/j.atmosres.2018.12.026
10. Gulia S, Shrivastava A, Nema AK, Khare M (2015) Assessment of urban air quality around a heritage site using AERMOD: a case study of Amritsar City, India. Environ Model Assess 20(6):599–608. https://doi.org/10.1007/s10666-015-9446-6
11. Gultepe I, Tardif R, Michaelides SC, Cermak J, Bott A, Bendix J, Muller MD, Pagowski M, Hansen B, Ellrod G, Jacobs W, Toth G, Cober SG (2007) Fog research: a review of past achievements and future perspectives. Pure Appl Geophys 164(6–7):1121–1159
12. Gupta S, Gadi R, Mandal TK, Sharma SK (2017) Seasonal variations and source profile of n-alkanes in particulate matter (PM_{10}) at a heavy traffic site, Delhi. Environ Monit Assess 189(1):43. https://doi.org/10.1007/s10661-016-5756-7
13. Guttikunda SK, Nishadh KA, Jawahar P (2019) Air pollution knowledge assessments (APnA) for 20 Indian cities. Urban Clim 27:124–141. https://doi.org/10.1016/j.uclim.2018.11.005
14. Jain S, Sharma SK, Choudhary N, Masiwal R, Saxena M, Sharma A, Mandal TK, Gupta A, Gupta NC, Sharma C (2017) Chemical characteristics and source apportionment of $PM_{2.5}$ using PCA/APCS, UNMIX, and PMF at an urban site of Delhi, India. Environ Sci Pollut Res 24(17):14637–14656. https://doi.org/10.1007/s11356-017-8925-5
15. Jain S, Sharma SK, Vijayan N, Mandal TK (2020) Seasonal characteristics of aerosols ($PM_{2.5}$ and PM_{10}) and their source apportionment using PMF: a four year study over Delhi, India. Environ Pollut 262:114337. https://doi.org/10.1016/j.envpol.2020.114337
16. Ji H, Shao M, Wang Q (2020) Contribution of Meteorological Conditions to Inter-annual Variations in Air Quality during the Past Decade in Eastern China. Aerosol Air Qual Res 20(5):1. https://doi.org/10.4209/aaqr.2019.12.0624
17. Kaur S, Senthilkumar K, Verma VK, Kumar B, Kumar S, Katnoria JK, Sharma CS (2013) Preliminary analysis of polycyclic aromatic hydrocarbons in air particles (PM10) in Amritsar, India: sources, apportionment, and possible risk implications to humans. Arch Environ Contam Toxicol 65(3):382–395. https://doi.org/10.1007/s00244-013-9912-6
18. Krishna KR, Beig G (2018) Influence of meteorology on Particulate Matter (PM) and vice versa over two Indian metropolitan cities. Open J Air Pollut 7:244–262. https://doi.org/10.4236/ojap.2018.73012
19. Kumar S, Nath S, Bhatti MS, Yadav S (2019) Chemical characteristics of fine and coarse particles during wintertime over two urban cities in North India. Aerosol Air Qual Res 18(7):1573–1590. https://doi.org/10.4209/aaqr.2018.02.0051
20. Li X, Jin L, Kan H (2019) Air pollution: a global problem needs local fixes. Nature 570:437–439. https://doi.org/10.1038/d41586-019-01960-7
21. Luan T, Guo X, Guo L, Zhang T (2018) Quantifying the relationship between $PM_{2.5}$ concentration, visibility and planetary boundary layer height for long-lasting haze and fog–haze mixed events in Beijing. Atmos Chem Phys 18(1):203–225. https://doi.org/10.5194/acp-18-203-2018
22. Meng C, Cheng T, Bao F, Gu X, Wang J, Zuo X, Shi S (2020) The impact of meteorological factors on fine particulate pollution in Northeast China. Aerosol Air Qual Res. https://doi.org/10.4209/aaqr.2019.10.0534
23. National Oceanic and Atmospheric Administration (2017) Surface weather observations and reports, Federal Meteorological Handbook No. 1, 98 pp. [Available from U.S. Department of Commerce, NOAA, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Maryland. https://www.ofcm.gov/publications/fmh/FMH1/FMH1_2017.pdf. Accessed 20 Aug 2020
24. Navinya CD, Vinoj V, Pandey SK (2020) Evaluation of $PM_{2.5}$ surface concentrations simulated by NASA's MERRA Version 2 Aerosol reanalysis over India and its relation to the air quality index. Aerosol Air Qual Res 20:1329–1339. https://doi.org/10.4209/aaqr.2019.12.0615
25. Pant P, Shukla A, Kohl SD, Chow JC, Watson JG, Harrison RM (2015) Characterisation of ambient $PM_{2.5}$ at a pollution hotspot in New Delhi, India and inference of sources. Atmos Environ 109:178–189. https://doi.org/10.1016/j.atmosenv.2015.02.074
26. Quan J, Zhang Q, He H, Liu J, Huang M, Jin H (2011) Analysis of the formation of fog and haze in North China Plain (NCP). Atmosp Chem Phys Discuss 11(4):11911–11937. https://doi.org/10.5194/acpd-11-11911-2011
27. Ram K, Sarin MM (2015) Atmospheric carbonaceous aerosols from Indo-Gangetic Plain and Central Himalaya: impact of anthropogenic sources. J Environ Manag 148:153–163. https://doi.org/10.1016/j.jenvman.2014.08.015
28. Ravindra K, Singh T, Mor S, Singh V, Mandal TK, Bhatti MS, Gahlawat SK, Dhankar R, Mor S, Beig G (2019) Real-time monitoring of air pollutants in seven cities of North India during crop residue burning and their relationship with meteorology and transboundary movement of air. Sci Total Environ 690:717–729. https://doi.org/10.1016/j.scitotenv.2019.06.216
29. Road accidents in India, 2017 report by Ministry of road transport and highways, Government of India. http://www.indiaenvironmentportal.org.in/files/file/road%20accidents%20in%20India%202017.pdf. Accessed 21 Aug 2019
30. Saraswat A, Kandlikar M, Brauer M, Srivastava A (2016) $PM_{2.5}$ population exposure in New Delhi using a probabilistic simulation framework. Environ Sci Technol 50(6):3174–3183. https://doi.org/10.1021/acs.est.5b04975

31. Sharma SK, Mandal TK (2018) Five-year measurements of ambient ammonia and its relationships with other trace gases at an urban site of Delhi, India. Meteorol Atmos Phys 130(2):241–257. https://doi.org/10.1007/s00703-017-0512-2
32. Wang N, Zhu H, Guo Y, Peng C (2018) The heterogeneous effect of democracy, political globalisation, and urbanisation on $PM_{2.5}$ concentrations in G20 countries: evidence from panel quantile regression. J Clean Prod 194:54–68. https://doi.org/10.1016/j.jclepro.2018.05.092
33. Xu L, Batterman S, Chen F, Li J, Zhong X, Feng Y, Rao Q, Chen F (2017) Spatiotemporal characteristics of $PM_{2.5}$ and PM_{10} at urban and corresponding background sites in 23 cities in China. Sci Total Environ 599:2074–2084. https://doi.org/10.1016/j.scitotenv.2017.05.048
34. Xu G, Jiao L, Zhang B, Zhao S, Yuan M, Gu Y, Liu J, Tang X (2016) Spatial and temporal variability of the $PM_{2.5}/PM_{10}$ ratio in Wuhan, Central China. Aerosol Air Qual Res 17(3):741–751. https://doi.org/10.4209/aaqr.2016.09.0406
35. Yadav M, Sahu SP, Singh NK (2019) Multivariate statistical assessment of ambient air pollution in two coalfields having different coal transportation strategy: a comparative study in Eastern India. J Clean Prod 207:97–110. https://doi.org/10.1016/j.jclepro.2018.09.254