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AN ANALYSIS TO UNDERSTAND THE AIR QUALITY PATTERN OF NORTH INDIAN CITIES

ERA UPADHYAY[1*], JHUMOOR BISWAS[2], MUGDHA NAYAK[3], SAIKAT GHOSH[4], P. CHAITANYA[1] AND MANALI DATTA[1]

[1]*Amity University Rajasthan, Jaipur, India*
[2]*Indian Institute of Social Welfare and Business Management, Kolkata, India*
[3]*Independent Researcher, Cupertino, USA*
[4]*Ohio University, Athens, Ohio, USA*

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ABSTRACT

Elevated aerosol concentrations extend to large densely populated cities of North India in addition of Delhi. In this study, Delhi and Lucknow are chosen as representative cities of urban North India and air quality is inter-compared for both intra-city and inter-city using statistical analyses to understand patterns of air pollutants, and gauge the extent of air pollution problem in North India. The average annual concentrations of $PM_{2.5}$ range from 127 µg/m^3 (Lucknow) to 140 µg/m^3 (Delhi) far exceeding the NAAQS standards for all site categories; 24-hr average standards for particulate matter are also exceeded. $PM_{2.5}$ concentrations of Lucknow match those of Delhi both in magnitude and distribution indicating impact of transboundary pollution as well.

KEY WORDS : Delhi, Lucknow, $PM_{2.5}$, SO_2, NO_2

INTRODUCTION

An amalgamation of inimitable geography and increasing emissions has caused deterioration of air quality in most places across the entire Indo-Gangetic plain, that includes major cities of North India like Delhi, Lucknow, Kanpur etc. These urban assemblages are subjected to major air polluters such as industrial activity, land use changes, vehicles and coal-fired power plants, burning of agricultural waste and garbage, as well as combustion of dung and other fuels for cooking and heating that has led to rapid degradation of air quality across North Indian region (Ram *et al*., 2010). Geography plays a major role in loading of the pollution in Indo-Gangetic pollution hotspots which is landlocked with the Himalayas mainly blocking air pollution from evasion to the North and creates a valley effect. There are seasonal impacts as well like spring season brings dust flows from Thar Desert adding particulate matter; while in winter, the air calms and shallow boundary layer confines the pollution to the earth's surface (Abish *et al.*, 2007) with predominance of aerosols from crop fires and industries. Biomass burning due to crop harvesting and a common practice of wood fuel burning for domestic use add to aerosol concentrations. This problem is accentuated in large parts of Northern India by a blend of fog, large concentrations of aerosols and strong meteorological inversions especially in winter. Transportation at regional level from neighboring states of Punjab and Haryana may have a significant impact as well on the pollution levels of these cities (Ghosh *et al.,* 2015).

Sulphur dioxide (SO_2) and nitrous oxide NO_x ($NO + NO_2$) are emitted from tall stacks of industrial point sources and coal-fired thermal power plants, and NOx can be transported several kilometers downwind with buoyant plumes released from stacks. NO_x is also emitted by heavy-duty vehicles burning diesel fuel. Aerosols in the atmosphere can result from direct emissions of emissions (or emissions of particulate precursors (NO_x, SO_2 and NH_3) which are partly transformed into particles by

***Corresponding author's email:** era.upadhyay@gmail.com

chemical reactions in the atmosphere (secondary PM). Several studies have reported the strong association of fine particulate matter with respiratory and cardiopulmonary disease, rising mortality (HEI, 2018; Mostofsky *et al.,* 2012) and increase in hospital admissions and emergency visits to hospitals (Capraz *et al.,* 2017) with intensifying air pollution levels. Air pollution has dramatically increased over the past decade with global annual PM levels raised by 6% during the recent three-year periods, i.e. 2009 to 2012 (WHO, 2018). Elevated level of particulate matter affects the human health causing mounting fatalities in China and India (HEI, 2018) retracting improvement in socio-economic conditions in these countries (Fotourehchi , 2016). The Indo-Gangetic region accounts for a large part (~42%) of the estimated mortalities and lost life expectancy was reported as 3.4±1.1years all over India with highest values found for Delhi (6.3±2.2years) (Sachin *et al.,* 2016). An estimated 3.7 million premature deaths are attributed to ambient (outdoor) air pollution out of which 10000 to 30000 deaths/annum were reported in Delhi alone (WHO, 2014). The health impact of air pollutants especially aerosols was reported to be extremely significant in polluted urban regions of India (Upadhyay, 2014) since they frequently exceed national ambient air quality standards in these regions (CPCB, 2012, Upadhyay *et al.,* 2017, Verma *et al*., 2015) although daily concentrations of SO_2 and NO_x were mostly within the limit of 80 $\mu g/m^3$.

According to World Health Organization (WHO) global air pollution database, several north Indian cities belong to the list of most polluted cities in the world in terms of aerosol concentrations. Delhi, the national capital is already well-known for its pollution levels and is currently ranked 11th globally. Four of these cities are situated in the most populous state of India located in northern India, Uttar Pradesh. Lucknow, the capital of Uttar Pradesh is currently ranked 18th globally on this list (WHO, 2014). Therefore, metropolitan cities in northern India as a whole play a major role in the air pollution problem currently prevalent in India. Several studies reported incidences of respiratory diseases, mortality, morbidity and cardiovascular diseases in most of the major cities in India like Delhi (Nagpure *et al*., 2014; Rizwan *et al.,* 2013) and Lucknow (Prasad and Sanyal, 2016) that have increased considerably over the years due to excessive increase of aerosol concentrations, which show no signs of abating in the near future.

Keeping in view the harmful health impacts on the citizens of Delhi and Lucknow in the context of rising air pollution concentrations, the present study is carried out to evaluate current status of air quality in selected industrial, residential and commercial sites of Delhi and Lucknow in the following aspects: to establish and understand site-to-site variability of aerosols; to evaluate their seasonal and annual variability and identify local and regional sources contributing to high particulate matter concentrations. Delhi and Lucknow have similar seasonal characteristics with summer (March-June), monsoon (July-October) and winter (January, February, November and December) seasons occurring in similar months. Air quality management strategies developed in these urban metro cities with burgeoning populations will have enormous implications on the future development of other Indian urban cities as well. In this context, the current air quality data analyses conducted in this paper with recent data available will enable to develop a better understanding of the current magnitude and complexity of air quality problem in northern India through a study of these representative cities and aid in development of effectual control strategies both on local and on a regional scale.

Study area

Delhi (latitude 20^0 4'N and longitude 77^{o}2'E), is located in central India, covering 1483 km. It is the capital of India and third most populated city in India with a population of more than 16 million. Lucknow is the largest city of Uttar Pradesh with population of 3.6 million. Naturally, this has caused environmental stress and elevated atmospheric concentration levels of aerosol. The city is situated between 26^{0}52'N latitude and 80^{0}56'E longitude at an elevation of approximately 123 meters above sea level and covers an area of 2,528 square km. Despite some emission control policies to curb emissions, such as fuel substitution, establishment of alternative modes of transport such as the metro both exhibit significant aerosol exceedances.

We have selected locations in Delhi and Lucknow (Figure 1) for our study that embraces all categories (residential, commercial and industrial) for (2016-2017) as per data availability. Delhi and Lucknow are located almost entirely on the Indo-Gangetic plain in a semiarid climate zone, with long summers and extremely foggy winters (Guttikunda and Gurjar, 2012). In winter, the synoptic patterns feature high pressure contours, stagnant conditions due to shallow mixed layer caused by inversion (average planetary boundary layer height between 800 m to 1.2 km), resulting in poor ventilation within mixed layer. This results in foggy conditions and extreme accumulation of aerosol concentrations over urban regions of North India.

Monitoring sites at Lucknow : The commercial areas are situated in the city where large amounts of pollution occur due to two wheelers and thee wheelers. Talkatora area has groups of small and medium industries such as manufacturing, paint etc. which collectively emit significant air pollutants (Figure 1).

Monitoring sites at Delhi : Out of two sites in Delhi, Anand Vihar is a posh residential area and a fast-developing commercial center in East Delhi District. Sahibabad industrial area and Patparganj industrial area are in close proximity. Towards east direction, UP border is just 100 m away from the monitoring site. The main road, Ghazipur road connects to National Highway-24. Overall, the study zone can be defined as industrial-cum-commercial zone with less residential activities. However, due to proximity to Inter-State Bus Terminus (ISBT), movement of traffic is relatively high. Another study site of Delhi is RK Puram, a residential colony in South West Delhi houses many high-profile corporate families. RK Puram comprises of many educational institutions, two weekly markets on Friday and Sunday and is well connected to different parts of the city by buses run Delhi Transport Corporation, Delhi is located west-north-west from Lucknow (Figure 1).

METHODOLOGY

Data availability

The air quality of two cities was analyzed with criteria air pollutants viz. NO_2, SO_2, and $PM_{2.5}$ for the years 2016 and 2017. Air quality data at 1-hour intervals for two sites of Delhi was obtained from official website of Delhi Pollution Control Board (DPCC) (https://dpcc.delhigovt.nic.in) and Openaq platform (https://openaq.org). Since SO_2 concentrations were much below National Ambient Air Quality Standards (NAAQS) at both cities, the data evaluation was focused principally on aerosols and NO_2 air pollutants.

The data at both observational sites in Delhi and Lucknow satisfy monitoring guidelines of Central Pollution Control Board of India (CPCB), which is a

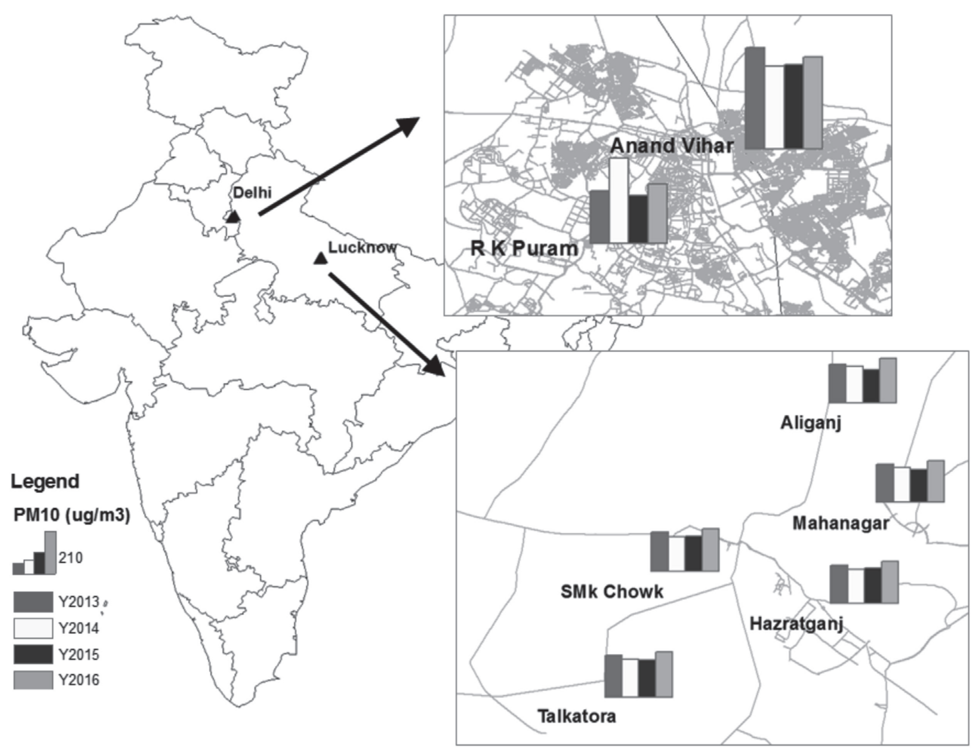

Fig. 1. Map of India depicting monitoring sites in Delhi & Lucknow and spatial distribution of annual averaged PM_{10} concentrations.

regulatory organization under the Ministry of Environment, Forest and Climate mandates that frequency of monitoring at a particular site must be at least twice a week for 104 days in a year. The operations and maintenance of monitoring sites in Lucknow and Delhi are undertaken by their respective pollution control boards. As per CPCB norms, the National Ambient Air Quality Standards (NAAQS) for 24-h averages and annual averages for SO_2 are 80 µg/m^3 and 50 µg/m^3 respectively while for NO_2, limits are 80 µg/m^3 and 40 µg/m^3 respectively. For $PM_{2.5}$, the standards are 60 µg/m^3 (24-h average) and 40 µg/m^3 (annual average). According to CPCB norms in case of various ambient air pollutants control procedures for air sampling and monitoring sections include, calibration of equipment and analyses of blank sample results to identify and isolate sources of contamination initiated in the field or the laboratory. Quality Assurance is reanalyzed by selecting 5-10% samples. Monitoring Equipment for SO_2 and NO_2 is the vacuum pump capable of maintaining a vacuum of ≤ 0.6 atmospheres across the flow control device and calibrate the flow measuring device to control the airflow from 0.2 to 1 l/min. Particulate matter is measured by high volume sampler with size selective inlet for PM and automatic volumetric flow control and calibrate flow-measuring device to control the airflow at 1132 l/min. Detection limit and working range for each pollutant follow the working instrument (CPCB, 2013).

Meteorological observational data such as temperature, wind speed, wind direction, relative humidity and precipitation were obtained from meteorological stations for both Delhi and Lucknow for the same time period from the website https://www.worldweatheronline.com.

Data Analysis

The examination of hourly, 24-hour, monthly averages and annual averages for Delhi and Lucknow was carried out to analyze the behavioral pattern in the datasets for each air pollutant. The analyses included diurnal and seasonal patterns, mean, standard deviations and coefficient of variation to understand data variability for each of the selected sites. In addition, percentiles were calculated to understand characteristics of data distribution. T-test and analysis of variance (ANOVA) (both tests applicable to variables that are random and normally distributed) were used to assess significance in differences in site to site concentrations. The measure of coefficient of variation (standard deviations normalized by mean values) for all sites was used to determine variability of data and to find out reasons of specific distinctions if any. Pearson's correlation coefficient was used to gauge correlation and degree of association between respective concentrations. The spatial heterogeneity was determined by coefficient of divergence defined as:

$$COD_{fn} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{if} - x_{ih}}{x_{if} + x_{ih}}\right)^2}$$

Where, x_{if} and x_{ih} are the concentrations of one species for the ith time period at sites f and h, respectively, and n is the number of observations. Values approaching 0 represent uniformity between pairs of samples, while values approaching 1 represent complete divergence (Kim *et al.*, 2015). Previous studies (Krudysz *et al.*, 2009, Wongphatarakul *et al.*, 1998) deduced a boundary COD value of 0.2, where COD values > 0.20 are defined as heterogeneous spatial distribution and values < 0.20 represent spatially homogeneous air pollutants.

RESULTS AND DISCUSSION

Diurnal Averages

Diurnal averages of air pollutants in Delhi and Lucknow were determined for an appraisal of intercity diurnal variations in air quality. The patterns determined from hourly concentrations help to understand the short-term cyclical system in air pollution concentrations over the course of a day and can provide important insights into information on local as well as regional pollution emission sources (Zhang *et al.*, 2015). Figure 2 depicts diurnal variations of $PM_{2.5}$ concentrations for Delhi and Lucknow sites for the year 2017.

Diurnal variations are almost similar for $PM_{2.5}$ and NO_2 for Delhi and Lucknow with higher concentrations in morning hours between 8-11 am and in late evening hours between 5-9 pm that clearly indicate the effect of rush- hour traffic. The rising concentrations of both pollutants till late night hours indicate influence of diesel fuelled trucks travelling on major roadway arteries and roadside dust that impact the air pollutant concentrations especially in Delhi. Delhi and Lucknow exhibit high $PM_{2.5}$ concentrations of 160 µg/m^3 (Delhi) and 120

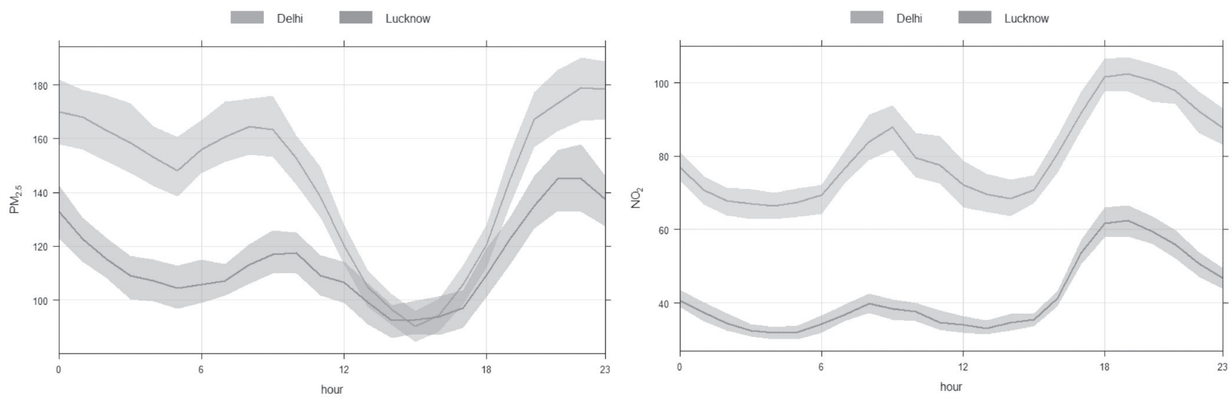

Fig. 2(a). Diurnal averages of $PM_{2.5}$ (b) Diurnal averages for NO_2

µg/m³ (Lucknow) during daytime peak hours and around 180 µg/m³ (Delhi) and around 140 µg/m³ (Lucknow) during late night hours. NO_2 concentrations in Delhi are distinctly higher than that of Lucknow with concentrations exceeding the standard of 80 µg/m³during the traffic rush hours in morning late night. Diurnal concentrations of NO_2 in Lucknow reached 60 µg/m³ during the night which although is within prescribed limits is still harmful for health. The concentrations of $PM_{2.5}$ and gaseous NO_2 from primary emissions were low in the afternoon, which corroborate results of earlier studies (Zhao *et al.,* 2016). Noticeable increases in aerosol concentrations after 1:00 am may be attributed to the build–up of particulates under inversion conditions (Zhao *et al.,* 2016; Srimuruganandam and Nagendra, 2010).

Percentiles and Coefficient of Variations for $PM_{2.5}$ for Delhi and Lucknow

We described the long-term benchmark concentration trends for a pollutant by analyzing 25th, 50th, 75th and 90th percentiles for 24-hr averaged concentrations to describe characteristics of data distributions (Table 1). The percentiles mean and coefficient of variations were determined for $PM_{2.5}$ (2016-2017) for Delhi and Lucknow averaged across all sites and all seasons (winter, summer and monsoon). Delhi has significantly higher concentrations than Lucknow in all percentile categories.

For Delhi and Lucknow, the highest seasonal mean PM concentrations were observed during winter though other seasons also exhibit high concentrations (Table 1). Both Anand Vihar and RK Puram have high aerosol concentrations. Talkatora, an industrial site of Lucknow, has the highest concentrations in all percentile categories followed by SMK Chowk which is a commercial area situated in the heart of the city where large amounts of air pollution occur due to two wheelers and three wheelers (details not shown). Both cities, i.e. Delhi and Lucknow show consistently high values of $PM_{2.5}$ in all percentile categories that exceed standards (Table 1). The coefficients of variation at both cities indicate similar patterns of high relative variability. These sorts of results are expected from heterogenic sources and the variability in concentrations would make it difficult to devise effectual control strategies for $PM_{2.5}$ concentrations.

Wind patterns

Table 1. Percentiles, means and coefficient of $PM_{2.5}$ variation for Delhi and Lucknow sites during 2016-2017

City	Parameter	Years	
		2016	2017
Delhi	90th Percentile	322	299
	75th Percentile	184	189
	25th Percentile	57	62
	Mean	143	140
	Coefficient of Variation	79	72
Lucknow	90th Percentile	254	229
	75th Percentile	146	163
	25th Percentile	23	52
	Mean	101	119
	Coefficient of Variation	85	64

The pollution rose illustrates the frequency distribution of wind direction temporally associated with $PM_{2.5}$ concentrations. The pollution rose plots drawn from the wind observations and $PM_{2.5}$ data at Delhi and Lucknow for representative year 2016-2017 are depicted in Figure 3. The pre-dominant wind and direction is from North West. In case of Delhi more than 30% of the total readings for the year lie above 250 μg/m³ and for Lucknow this distribution is between 25% and 30% from northwest direction indicating that the majority of Delhi's and Lucknow's particulate matter is coming from the north-west direction. The color sectors also reveal high concentrations from south west and south east though around 10%. Figure 3 denotes the predominant wind directions in 2015 for different seasons, Winds from WNW direction were observed on maximum numbers of days i.e. 45% in winters followed by 28.9% in summer and 25.4% in monsoon days. The above analysis reveals that predominant local wind directions are

WNW and NW for both Delhi and Lucknow with lower wind speeds in winter that creates anticyclonic weather conditions causing descending air currents that prevents vertical mixing. The two sets of independent data analyses reconfirm that prevailing transport patterns are similar for both Delhi and Lucknow for all years.

Monthly Averages

Delhi and Lucknow reflect distinct seasonality in $PM_{2.5}$ concentrations with highest values occurring in winter and lowest during monsoon. Both sites of Delhi exhibit consistent higher values than sites in Lucknow for all seasons and for all years (Figure 4). The $PM_{2.5}$ concentrations for Delhi in 2017 are high daily in November around reaching 380μg/m³. December and January also reveal high concentrations of $PM_{2.5}$ in Delhi. Even in summer, values at Anand Vihar occasionally reached 400μg/m³ for a single day average during this time period showing significance of local emissions. Emissions of ammonia (NH_3) from agricultural and other sources also contribute to particulate matter formation during the summer months (Lawson & Smith, 1998). In Lucknow, although concentrations are lower than Delhi, values markedly exceed 200μg/m³ in winter. The $PM_{2.5}$ concentrations are highest around 250μg/m³ in November. $PM_{2.5}$ monthly averaged distribution of Delhi and Lucknow are very similar disclosing the prevalent nature of $PM_{2.5}$ distribution influenced by synoptic forcings in North India. High winter averages of aerosols occur due to limited pollutant dispersion caused by formation of high-pressure system, which results in lower mixing heights with stable boundary layer. Lucknow's air quality is impaired with increasing traffic, construction activities, including work on metro and smoke from brick kilns. The industrial region of Talkatora has highest concentrations during all

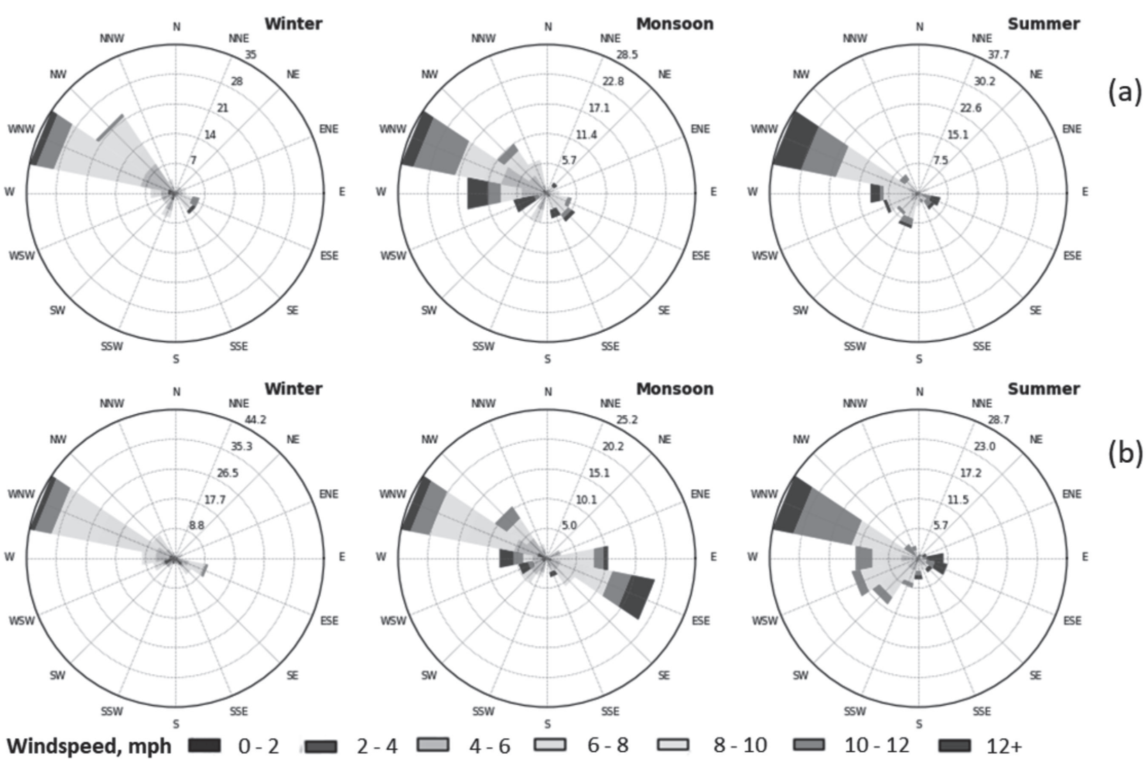

Fig. 3. Wind Rose plots of all seasons of year 2015 for (a) Delhi and (b) Lucknow.

seasons in Lucknow. As expected, the monsoon months (mid-June-September) have lower concentrations though sometimes still exceeding limits for both Delhi and Lucknow. The primary reasons for Delhi's and Lucknow's considerably high aerosol concentrations is that Delhi has highest number of vehicles (about 10 million vehicles) and no. of vehicle registrations and number of two-wheelers has increased substantially in Lucknow. Parts of the traffic also consist of unregulated transit traffic from neighboring states as well. Construction activities also contribute substantially to air pollution. Delhi is surrounded by a massive rural hinterland where biomass is burnt in large quantities as both fuel and waste clearance. Delhi's neighboring states Haryana, Punjab and Western UP comprise of huge industrial areas and Delhi's environs have a large number of industries, especially coal power plants. Trans-boundary pollution in Delhi comes from neighboring states of Punjab, Haryana and Uttar Pradesh (Mohan, 2013) and local transport of air pollutants from surrounding NCR region (HEI, 2018) is quite significant. The results also show that in spite of having less local emission sources, Lucknow is catching up to Delhi in terms of aerosol concentrations mostly because of increasing urbanization and trans-boundary air pollution.

Annual Averages

Annual averages of aerosol concentrations help to understand long-term impact of air pollutants. Annual averages of $PM_{2.5}$ concentrations have been computed from available data for 2016-2017. Annual averages of Delhi vary between 161µg/m^3 to 143 µg/m^3 at Anand Vihar to around 134 µg/m^3 at RK Puram for both years. The annual averaged concentrations at Lucknow vary between 127 µg/m^3 at Talkatora and 121µg/m^3 at SMK Chowk in 2017 to around 101µg/m^3 in 2016 and 107 µg/m^3 in 2017 at Hazratganj. What is noticeable is that annual averaged concentrations at Lucknow are in similar concentrationsrange to those of Delhi. Both cities do not show much inter-annual variability in case of $PM_{2.5}$ concentrations. The difference in annual averages of $PM_{2.5}$ concentrations ANOVA test results show that is not significant between Delhi and Lucknow from results of ANOVA testing. This reiterates the need of developing holistic mitigation strategies for both cities. The ineffectiveness of long-term mitigation measures to control aerosol concentrations is apparent in both cities.

Coefficient of Divergence

The spatial interrelations of daily-averaged concentrations of $PM_{2.5}$ were evaluated using Pearson correlation coefficients (r) and coefficients of divergence (COD). Pearson correlation coefficients show the degree of linear correspondence of the pollutants between two sampling sites. High r values (close to unity) indicate that concentrations of the sites are proportion throughout the sampling period. Delhi has a strong intra-city correlation of 0.9 for $PM_{2.5}$ in 2017 while Lucknow has an intra-city

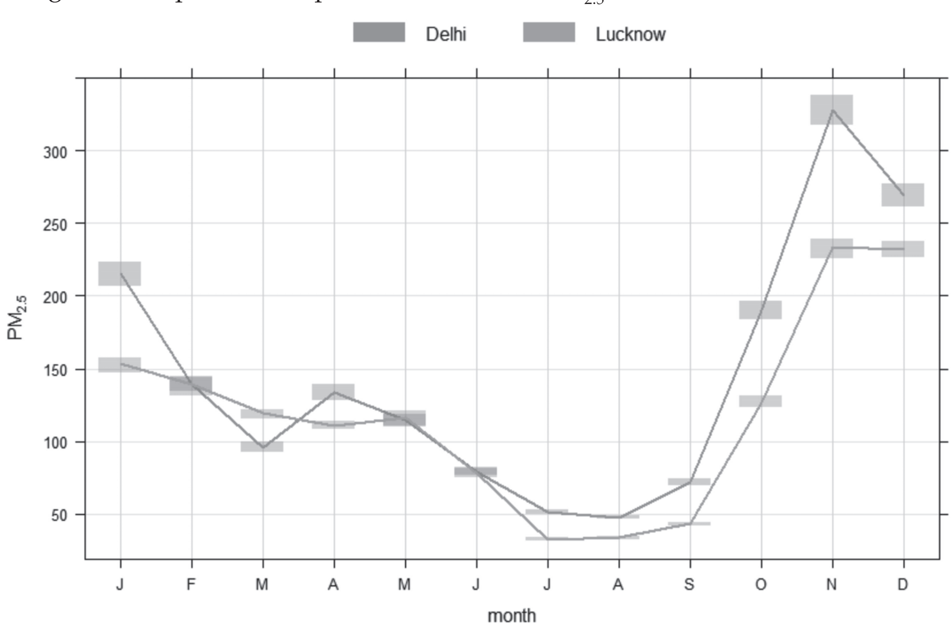

Fig. 4. Monthly averages of $PM_{2.5}$ (2016-2017) for Delhi and Lucknow.

correlation of 0.78. For $PM_{2.5}$, Delhi and Lucknow have a Pearson correlation coefficient of 0.7 revealing significant degree of association. COD is applied to further evaluate the similarity between concentrations at different monitoring sites. In case of Delhi and Lucknow, all the intra-city sites show strong correlations ($r^2 \geq 0.64$ and COD <0.2) depicting spatial homogeneity between all sites and for all years. Delhi and Lucknow intercity sites COD for is 0.3 which shows that transportation affects ($PM_{2.5}$ being light can travel long distances), the levels and patterns of $PM_{2.5}$ concentrations, which are similar in Delhi and Lucknow.

This is borne out by the distribution of concentrations in the percentile (Table 1) as well as the daily concentrations of $PM_{2.5}$ shown above where Lucknow's concentrations patterns impersonate Delhi (Figure 6). This reemphasizes the fact the aerosol problem of North India cannot be treated in isolation but holistically amongst all North India cities. Delhi has larger number of emission sources.

Frequency Distribution for Delhi and Lucknow for $PM_{2.5}$

The frequency distributions of daily averaged $PM_{2.5}$ concentrations in Delhi and Lucknow (Figure 7) specify that distributions of $PM_{2.5}$ in the two cities are similar for the two seasons. In winter, both Delhi and Lucknow PM2.5 concentrations can sometimes go above 400µg/m^3. In summer and post-monsoon, values are mostly distributed in 250-300 µg/m^3 range. Thus the extent of geographical variability in case of $PM_{2.5}$ concentrations is much lower with Delhi and Lucknow displaying similarities in magnitude and distribution of concentrations. This analysis is consistent with earlier analysis that $PM_{2.5}$ concentrations in Delhi and Lucknow exhibit similar patterns of monthly averages principally because of dominant synoptic patterns and regional transport of $PM_{2.5}$ pollutants.

Relationship of ambient air quality with meteorological parameters and with chemical parameters for $PM_{2.5}$

The relationship between pollutants is depicted using linear regression. The coefficient of determination (R^2) values indicates the degree of relationship between variables. Local climatology data analysis reveals that the meteorological profiles of these two cities are similar with daily maximum temperatures reaching in upper 40^o C in both Delhi and Lucknow during summer months. The relative humidity content and precipitation patterns are similar in the two cities. Temperature has the most noticeable seasonal impact on aerosol concentrations. In winter, Delhi's aerosol concentrations are influenced significantly by biomass burning from neighboring Punjab from north-west. Higher temperatures in the tropics usually increase the quantity of biomass burning (Azmi *et al.*, 2010) and soil dust causing a rise in aerosol concentrations trapped by lower inversion layer.

In Lucknow, local emissions from road dust and

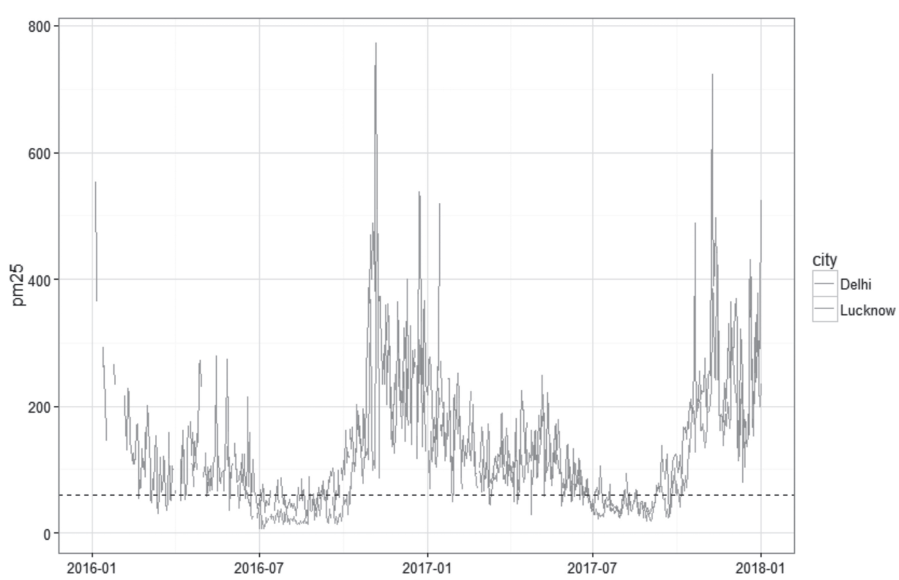

Fig. 6. Daily Concentrations of $PM_{2.5}$ (2016-2017) for Delhi and Lucknow.

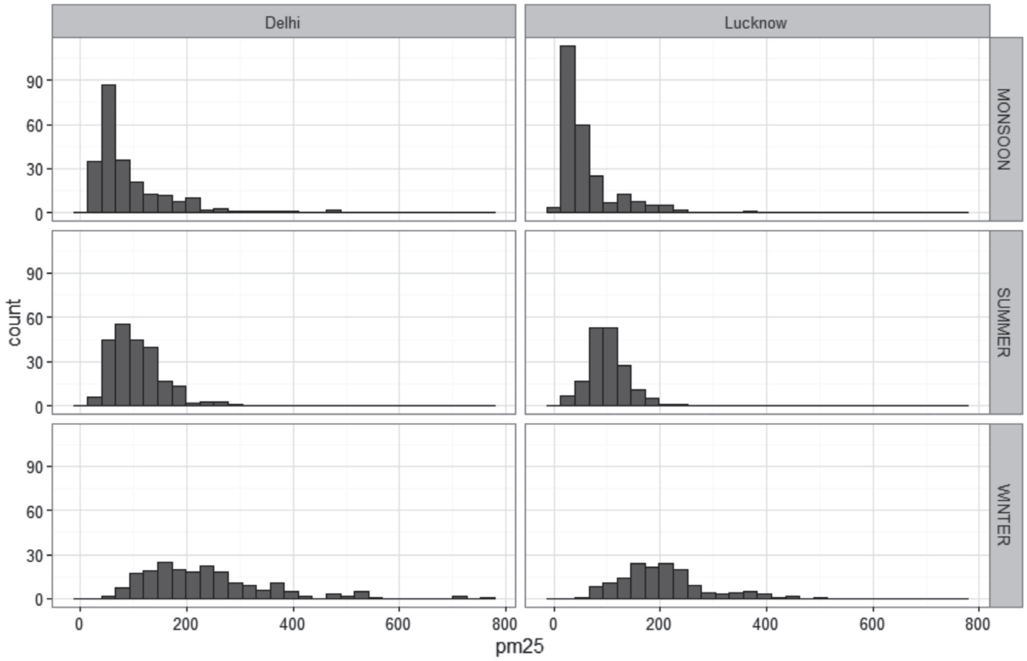

Fig 7. Frequency Distribution Patterns for $PM_{2.5}$

vehicular pollution dominate PM concentrations and higher temperatures cause more atmospheric dispersion and vertical mixing leading to lowering of concentrations. The turbulence in lower stable atmospheric layer causes more diffusion of aerosols in winter causing more significant correlations in this season. Figure 8 depicts the correlation plot for $PM_{2.5}$ with meteorological parameters and NO_2 for Delhi and Lucknow. Both Delhi and Lucknow exhibit small to negative correlations with wind speeds and quite noteworthy negative correlations with humidity (-0.3 - 0.5) for all seasons and all locations. Increased humidity may result in precipitation that scavenges aerosols from atmosphere (observed during post-monsoon) whereas strong winds cause more dispersion of air pollutants. $PM_{2.5}$ and NO_2 concentrations show positive correlation which is favorable to produce pollution. Temperature has a strong negative correlation with $PM_{2.5}$ concentration which may also reflect the seasonal variation in $PM_{2.5}$ concentration. Negative correlation between $PM_{2.5}$ concentrations and temperature might be due to the fact that high temperature promotes the convection of air which is the reason of dilution and dispersion of air pollutants while low temperature may lead to increased emission rates from domestic heating and power production (Luo *et al.*, 2017; Tran and Mölders, 2011). The results indicate the temperature and wind speed is positively correlated with $PM_{2.5}$ in winters.

Status of Air Quality in Delhi and Lucknow

In Delhi, an inter-comparison with results of previous study, reveal $PM_{2.5}$ concentrations have increased on an average of 20% in Delhi since 2009 caused by increasing multiple sources related to increased industrialization, urbanization and population densities which have caused increase in emissions from diesel engine exhaust, escalation in construction activities and uncontrolled waste burning.

The diurnal averages of criteria pollutants reveal that vehicular emissions strongly influence temporal variations of these pollutants. Weekdays and weekend diurnal averages did not show noticeable differences (Biswas *et al.*, 2011). Neighbouring states of Punjab (primarily biomass burning) and Haryana (mostly transit diesel trucks) as well as the NCR region of Delhiconsisting of (manufacturing industries, brick kilns, construction activities), also contribute significantly. In Lucknow, compared to previous studies (Verma *et al.*, 2015), the averaged 24-h $PM_{2.5}$ concentrations are increasing. Major contributors are air pollutants from traffic, road dust in residential and commercial sites, with additional emissions from medium-small scale industries as evident in Talkatora. Emissions are influenced by flow of interstate diesel vehicles.

In the past years, Government of India has released a slew of mitigation measures to control air pollution such as initiating control measures for vehicular pollution (stricter BS-IV emission norms in vehicles leading to decline of sulphur emissions and NOx emissions from gasoline and diesel run vehicles), fuel substitution such as the use of heavy-duty compressed Natural Gas engines (CNG) replacing diesel-fuelled engines for public transportation in Delhi, better traffic management such as expansion of metro in Delhi and introduction of metro in Lucknow, implementation of flue-gas desulphurization control for some power plants and creating awareness among public on environmental health hazards. The current study has re-confirmed that reduction of aerosol concentrations is still an enormous challenge in urban regions of North India. The $PM_{2.5}$ problem is a regional problem in north India with similarities in geographical distribution of high concentrations of $PM_{2.5}$ concentrations. This problem is aggravated with meteorological conditions favouring accumulation of $PM_{2.5}$ concentrations across north Indian cities. The problem is escalated by the fact that NO_x and SO_x emissions which form part of ever-increasing vehicular exhausts contribute to the production of secondary aerosols in a gas-to-particle conversion process.

Sources of $PM_{2.5}$

Since this study has identified the particulate matter ($PM_{2.5}$) as prominent pollutant in Delhi and Lucknow cities of North India, it is imperative to understand the sources to high pollutant concentrations for designing effective control strategies. Hao et al. quantified the contributions of eight source types to fine particulate matter ($PM_{2.5}$) and its components including primary PM (PPM) and secondary inorganic aerosol (SIA) including sulfate, nitrate and ammonium ions, in Delhi, Chandigarh, Lucknow and Jaipur by using source-oriented versions of the Community Multi-scale Air Quality (CMAQ) model with Emissions Database for Global Atmospheric Research (EDGAR) (Hao *et al.* 2017, Zhang *et al.* 2012, Srivastava *et al.* 2008, Zhang, Ying 2010). North Indian cities e.g. Delhi, Lucknow, dominated by primary PM emission from industry, residential activities and energy sectors, emissions energy sectors reach a maximum of 200 $\mu g/m^3$ during winter. Secondary inorganic aerosol concentrations from different sources are more heterogeneous. High secondary inorganic aerosol concentrations ($\leq 25\ \mu g/m^3$) at south Delhi and central Uttar Pradesh were mainly attributed to agriculture sector (Hao *et al.,* 2017).

CONCLUSION

On the basis of the results of analysis, it is being inferred that both of the cities- Delhi and Lucknow are polluted mainly by particulate matter. NO_2 and SO_2 concentrations have decreased mostly due to fuel switch and more industrial controls and are not considered in details in this study . However, aerosol concentrations are growing substantially and show

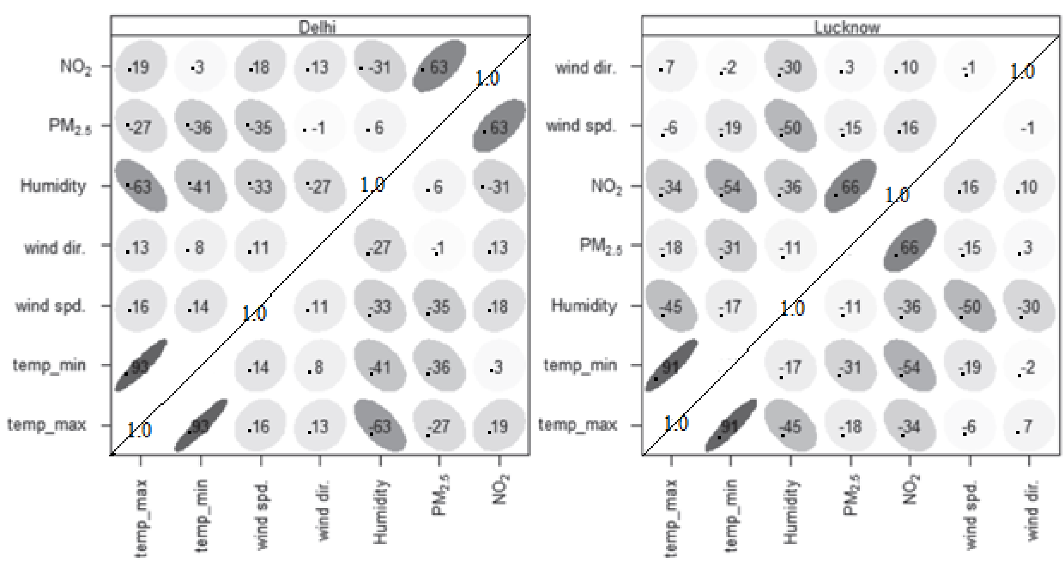

Fig 8. Correlation plots for $PM_{2.5}$ with Meteorological parameters and NO_2 for Delhi and Lucknow.

no emissions signs of abating. Aerosol sources like vehicular, industrial emissions, road dust, and crop burning emission, domestic and construction activities are on the rise with ever increasing population and urbanization.

The pearson's correlation coefficient between the concentrations at the two sites varies from 0.48 to 0.6 for all the years indicating some degree of association most likely due to seasonal influence. The acuity of $PM_{2.5}$ problem is enormous in both Delhi and Lucknow. Lucknow's $PM_{2.5}$ concentrations rival that of Delhi and this study clearly demonstrates that air quality is fast deteriorating in North Indian cities other than Delhi as well; the problem is further aggravated by meteorological interventions that add to the uncertainties of effective management of aerosol concentrations. The geographical patterns and distribution of $PM_{2.5}$ concentrations are similar in both cites exhibiting the regional nature of the problem. Gaseous pollutants have shown a significant decrease in Delhi and Lucknow as compared to earlier studies, although NO_2 concentrations sometimes exceed standards in Delhi. From health perspective, aerosol problem continues to be critical in both these major cities of North India. Emission reduction strategies related to prediction and protection of health must occur though synergy at national, regional and state levels. Regional emission control strategies involving all major cities situated in Indo-Gangetic plain in North India is critical to forestall the $PM_{2.5}$ problem rather than developing only localized emission controls. Strict emission controls must be invoked to combat with uncertainties in emissions inventory and meteorological impact through multi-effect approach.This includes comprehensive and judicious combination of observational and satellite data analysis, evaluation of emissions and meteorological variability, and long-term numerical modelling to develop effectual emission reduction strategies.

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