

Characteristics of near-surface air pollutants at an urban station in the central Indo-Gangetic Basin

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सार – तीन साल की अवधि (2015 से 2017) के दौरान एक शहरी स्टेशन लखनऊ में सतह के निकट वायु प्रदूषकों की मापों का आकाशीय और औद्योगिक, दो विपरीत स्थलों पर अध्ययन किया गया है। एक औद्योगिक स्थल पर सल्फर डाई ऑक्साइड (SO₂) नाइट्रोजन डाई ऑक्साइड (NO₂) नाइट्रिक ऑक्साइड (NO) और 2.5 (पी एम 2.5) से कम आकार के विविक्त पदार्थ की वार्षिक औसत द्रव्यमान सांद्रता लगभग 10 ± 5, 28 ± 17, 10 ± 11 और 128 ± 99 μgm⁻³ और आवासीय स्थल पर क्रमशः 8 ± 5, 30 ± 21, 9 ± 7 और 102 ± 81 μgm⁻³ थी। यह देखा गया कि पी एम 2.5 की वार्षिक औसत द्रव्यमान सांद्रता अपने वार्षिक राष्ट्रीय परिवेशी वायु गुणवत्ता मानकों (NAAQS) के स्तर से लगभग 3 गुना अधिक थी हालांकि SO₂ और NO₂ क्रमशः अपने वार्षिक NAAQS स्तरों से लगभग 5 और 1.5 गुना कम थे। दोनों स्थानों पर शीतऋतु / मानसूनोत्तर ऋतु के दौरान सभी प्रदूषकों की ऋतु की औसत द्रव्यमान संहिताएं उच्चतम देखी गईं जो आवासीय स्थलों की तुलना में औद्योगिक स्थलों पर अधिक स्पष्ट थीं। स्टेशन पर शीतकाल/ मॉनसूनोत्तर काल के दौरान प्रेक्षित उच्च प्रदूषक मुख्य रूप से उत्तर-उत्तर पश्चिम दिशा से वायु द्रव्यमान प्रक्षेप पथ के पीछे से संबद्ध पाए गए।

ABSTRACT. Measurements of near-surface air pollutants at an urban station, Lucknow have been studied at two contrasting sites as residential and industrial during three-year period from 2015 to 2017 to understand their variability on different temporal scales. The annual mean mass concentrations of sulphur dioxide (SO₂), nitrogen dioxide (NO₂), nitric oxide (NO) and particulate matter of size less than 2.5 μm (PM_{2.5}) at an industrial site were about 10 ± 5, 28 ± 17, 10 ± 11 and 128 ± 99 μg m⁻³ and at the residential site were about 8 ± 5, 30 ± 21, 9 ± 7 and 102 ± 81 μg m⁻³ respectively. It was observed that the annual mean mass concentration of PM_{2.5} was about 3 times higher than its annual National Ambient Air Quality Standards (NAAQS) level. However, SO₂ and NO₂ were about 5 and 1.5 times lower to their annual NAAQS levels, respectively. The seasonal mean mass concentrations of all the pollutants were found to be highest during the winter/post-monsoon season at both the sites, which are more pronounced at industrial site compared to residential site. The observed high pollutants over the station during the winter/post-monsoon season were found to be largely associated with the air mass back-trajectories from N-NW direction.

Key words – Particulate matter, Air quality, Indo-Gangetic basin, Residential and industrial site.

1. Introduction

Atmospheric aerosols are the chemically-active and complicated mixture of solid, liquid and gaseous particles, which have posed major environmental, climatic and health concerns in recent decades (Pope and Dockery, 2006; Guttikunda and Calori, 2013; Pauchauri *et al.*, 2013; Chowdhury and Dey, 2016). Urban population of the world has been increasing rapidly during last few decades. In 1950, about 18% of the world's population was living in urban areas, whereas in 2001, it was exceeded to about 50% (Gurjar *et al.*, 2016). In the year 2012, United Nation expected the increase in the world population from 7 to 9.3 billion from 2011 to 2050 and the urban areas of the

worlds to ingest all the population growth over this period. The major uses of energy in many forms cause high levels of air pollution in megacities (Ravindra *et al.*, 2015; Gurjar *et al.*, 2016; Deep *et al.*, 2019; Kishore *et al.*, 2019). In urban areas, plumes contain huge amount of different pollutants including aerosols and green-house gases, which affect atmospheric chemistry (Molina *et al.*, 2010, 2004; Kanakidou *et al.*, 2011; Gurjar *et al.*, 2016). World climate system can be affected by atmospheric aerosols through impacting the incoming solar radiation, re-distributing the Earth's energy budget, cloud microphysics and thereby precipitation pattern (Ramanathan *et al.*, 2001; Poaschl, 2005; Sarangi *et al.*, 2017; Kumar *et al.*, 2019; Kanawade *et al.*, 2020).

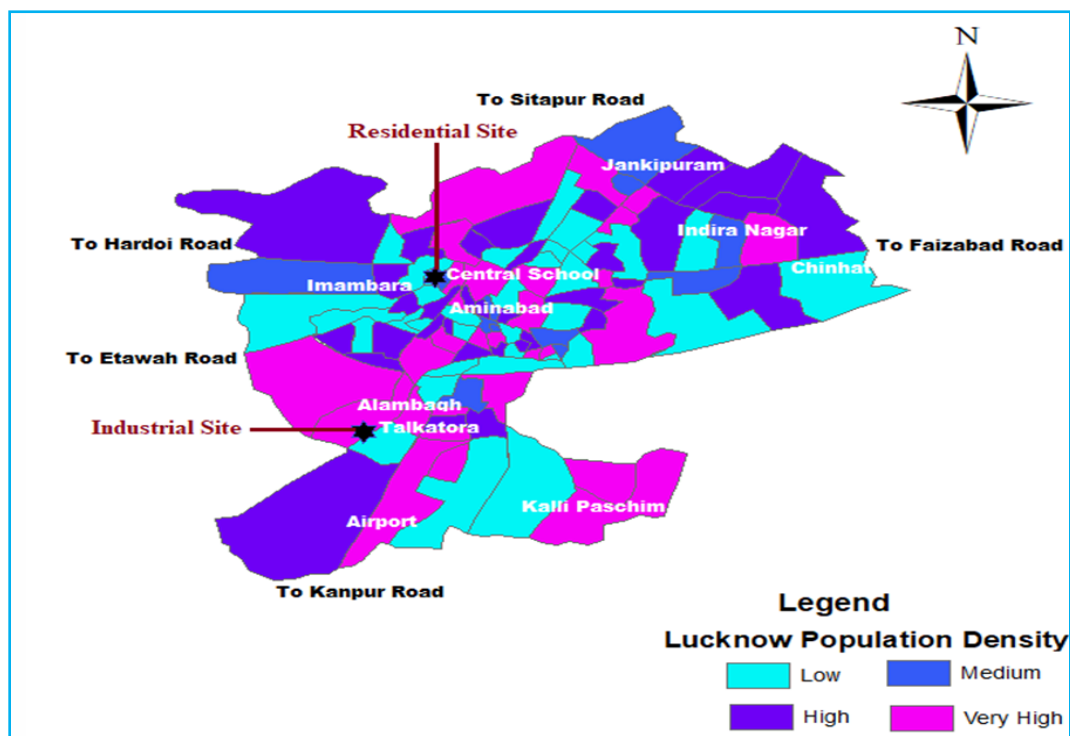


Fig. 1. Lucknow region showing the location of the measurement sites, Central School residential area and Talkatora industrial area along with the population density (filled colors)

World Health Organization (WHO) reported that 37 cities from India feature in the top 100 world cities with the worst $PM_{2.5}$ pollutions and the cities like Delhi, Lucknow, Gwalior and Raipur are recorded in the top 10 (WHO, 2014). In India, air quality is one of the major cause of concerns, particularly in urban megacities and the air pollutants including particulate matter (PM), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) etc. regularly exceed the National Ambient Air Quality Standards (NAAQS) (Guttikunda *et al.*, 2014). Many metro cities over the Indo-Gangetic Basin (IGB) are the most polluted cities in world. This combination of polluted cities in IGB makes it one of the world's most populated and polluted river basin (Dey and Di Girolamo, 2010). Lucknow is one of urban metro city situated in the central IGB. Few recent studies have shown that the emissions of particulate matter, SO_2 , NO_2 and NO in Lucknow are still increasing rapidly (Pandey *et al.*, 2012; Verma *et al.*, 2015; Pal *et al.*, 2018), which received much attention in the recent years as it poses potential health hazard (Dockery and Pope, 1994; Pope *et al.*, 1995; Pandey *et al.*, 2012; Verma *et al.*, 2015).

The air quality monitoring of Lucknow, in terms of particulate matter emissions, impact of compressed natural gas (CNG), air toxicity and air quality index have been carried out in the recent past but for the limited near

surface measurements (Pandey *et al.*, 2012; Verma *et al.*, 2015). However, in the present study, we have used three-years (2015-2017) near surface measurements of $PM_{2.5}$, SO_2 , NO_2 and NO at two contrasting sites at Lucknow (*i.e.*, residential and industrial) to examine their characteristics on different temporal scales.

2. Site description and meteorological condition

Lucknow (26.8° N, 80.9° E and ~ 128 meters above mean sea level) is bounded by the River Gomti that rambles through the city and partition it into the Trans-Gomti and Cis-Gomti regions. The city is placed in the central part of the IGB incircled by rural towns and villiages and situated under seismic zone III. The region covers about 310 km^2 and inhabited of about 2815033 (Census, 2011). The present study was carried out at the Central School, Aliganj and Talkatora sites, which are the representative residential and industrial sites of Lucknow, respectively. A population density map of Lucknow, indicating the location of the two contrasting measurement sites is shown in Fig. 1. It shows very high population density area surrounds the measurement site at Central School, Aliganj whereas Talkatora surrounds relatively low population density. The city has shown exceptional growth in its area over the years, *i.e.*, 143 sq km in 2001 to 310 sq km in 2011 (Verma *et al.*, 2015). Construction

of metro work and ring roads has opened the door for city development. The city has also shown approximately 10% growth in vehicular population over the last decades. The number of registered vehicle plying on roads was 422188 in the year 2000, 1107455 in 2010, 1552695 in 2014 and 2380935 in 2017 as per the records of Road Transport Office (RTO) Lucknow. Vehicular emissions and metro construction work are found to be highest contributor to total air pollution in Lucknow (CPCB, 2017). Lucknow region has a humid sub-tropical climate, with very cool dry winter from December to February and a hot summer from April to June. The temperature over the city varies from about 45 °C in the summer to 3 °C in winter. Lucknow receives about 1000 mm of annual rainfall mostly from the southwest monsoon between July and September.

3. Instrumentations and data analysis

Data presented in this work is obtained from Central Pollution Control Board (CPCB) for the residential area at Central School, Aliganj and industrial area at Talkatora in Lucknow from 2015 to 2017. Various criteria pollutants are being monitored at these sites, including sulphur dioxide (SO₂), nitrogen dioxide (NO₂), particulate matter with diameter <2.5 µm (PM_{2.5}) and nitric oxide (NO). Studies of PM_{2.5} have found a close link between exposure to fine particles and premature death from heart and lung diseases (Chowdhury and Dey, 2016). Fine particles are likewise known to worsen chronic or trigger ailments such as heart attack, asthma and other breathing disputes. PM_{2.5} data was measured using gravimetric, Tapered Element Oscillating Micro-balance (TEOM) and Beta attenuation method. An electrical air sampler draws encompassing air at a steady volumetric flow rate of 16.7 L min⁻¹. It kept up by a mass flow/volumetric flow controller coupled to microprocessor into exceptionally structured inertial molecule estimate go to separator where the suspended particulate matter in the PM_{2.5} territories is isolated for accumulation on a 47 mm poly tetra fluoro ethylene (PTFE) channel over a pre-defined inspecting period. Each filter is weighed before and after the sampling to find out the net gain due to the particulate matter. Ambient air mass concentration is calculated as the total mass of collected particles in the particulate matter size ranges, divided by the 2.5 actual volume of air sampled and written as µg m⁻³. The sampling time weighted average was carried out every 8-hours round the clock.

SO₂ is measured using the UV-Fluorescence method and modified West and Gaeke method. In order to detect SO₂ with this method, SO₂ in ambient air was mixed in 0.04 M sodium tetra chloromercurate solution at 1 L min⁻¹ average flow rate. Although the range of SO₂ achieved should have been 4-1050 µg m⁻³ but in normal condition the range achieved was 25-1050 µg m⁻³. It is possible to

measure lower concentrations by increasing the volume of air sample after finding the absorber efficiency of system satisfactory.

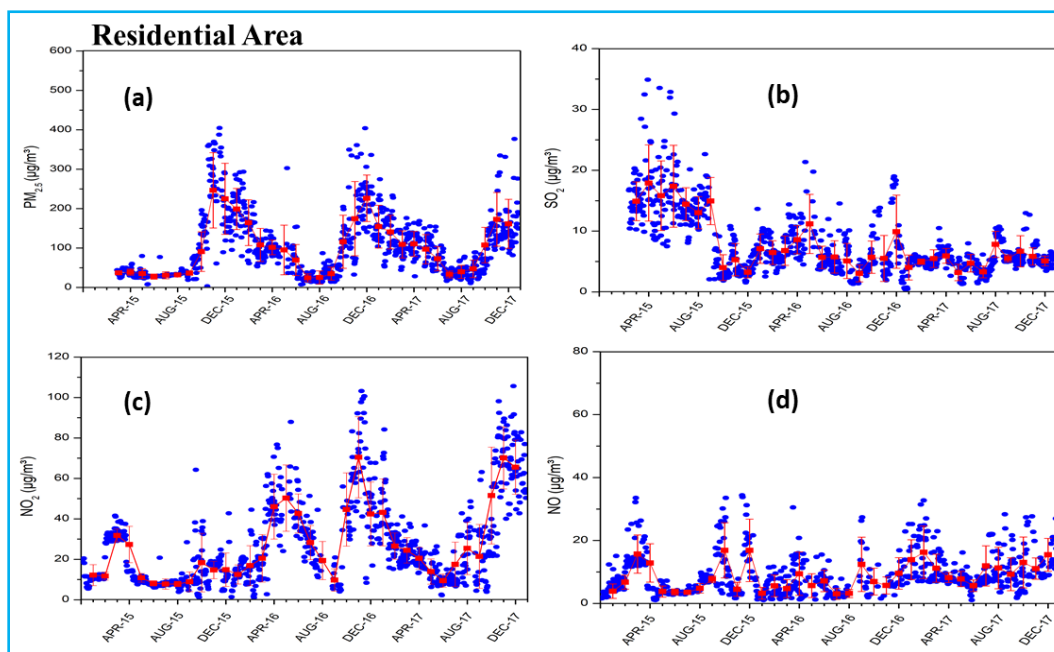
NO and NO₂ are measured using the Chemiluminescence Method where the Chemiluminescence analyser is a consolidation of an NO-NO₂-NO_x analyzer and NH converter. The converter is used to oxidize Ammonia to nitric oxide (NO). The sample air drawn from the converter into the NH analyser through a particulate filter, a glass capillary and a solenoid valve at a flow rate of 0.6 L min⁻¹. The 3 solenoid valve routes the sample either directly into the reaction chamber (NO mode), 24 through the molybdenum converter and the reaction chamber (NO_x mode), or through the ammonia converter and the reaction chamber, where ambient NO₂ is collected by bubbling air through a solution of sodium hydroxide and sodium arsenite, considering SO₂ as a major interfering compound. In this technique, chemical reaction derived absorbance of the coloured azo dye is measured on a spectrophotometer at a wavelength of 540 nm to determine the NO₂ in the sample in the range of 9 to 750 µg m⁻³. This method has an average bias of ~3% over the range of 50 to 300 µg m⁻³.

This study has used three years (2015-2017) of near-surface measurements of criteria pollutants (PM_{2.5}, SO₂, NO₂ and NO) from the Central School Aliganj (Residential Area) and Talkatora (Industrial Area) at Lucknow. Systematic analysis has been performed to examine daily, monthly, seasonal and inter-annual variability of the measured criteria pollutants. Further, clustered air mass trajectories from the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) PC-version model were analysed over the station to identify the potential source sectors for the measured criteria pollutants.

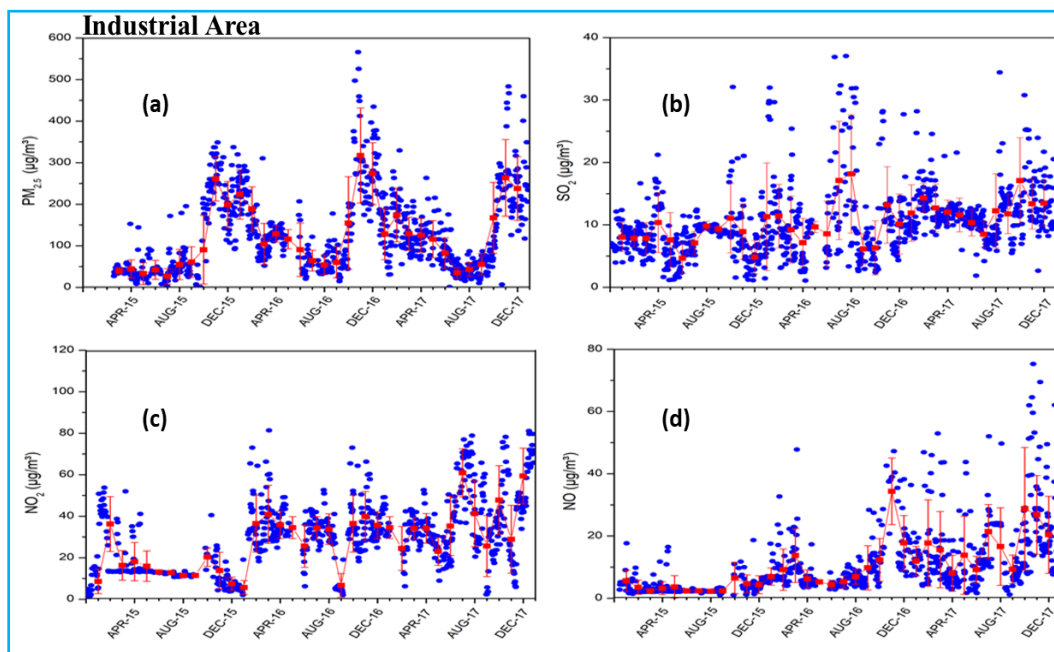
4. Results and discussion

4.1. Time series analysis of air pollutants

Figs. 2(a-d) & 3(a-d) show the daily and monthly mean time series of the measured near surface criteria pollutants at residential and industrial sites, respectively. Daily mean PM_{2.5} mass concentration at residential site was varying from 3.1 to 404.7 µg m⁻³, with mean concentration of 102.0 ± 84.5 µg m⁻³ whereas at industrial site from 0.5 to 607.2 µg m⁻³, with mean value of 127.5 ± 98.9 µg m⁻³ over the study period. The PM_{2.5} was found to be higher than its 24-hour NAAQS value (60 µg m⁻³) for about 58% of the days of total observation days at residential site and about 67% of the days of total observation days at industrial site. Pandey *et al.* (2012) calculated the emission of PM_{2.5} and PM₁₀ from various emission sources in Lucknow and observed these



Figs. 2(a-d). Daily (Blue dots) and monthly (Red dots) mass concentrations of (a) $PM_{2.5}$, (b) SO_2 , (c) NO_2 and (d) NO at Lucknow Residential area during the entire study period



Figs. 3(a-d). Daily (Blue dots) and monthly (Red dots) mass concentrations of (a) $PM_{2.5}$, (b) SO_2 , (c) NO_2 and (d) NO at Lucknow Industrial area during the entire study period

values about 101 and 204 $\mu g m^{-3}$, respectively during 2007-2008. In a recent study by Mukherjee and Agrawal (2018) at Varanasi (situated in the IGB and about 280 km away from Lucknow) during 2014-2017, the mean PM_{10} concentration was observed to be $\sim 245 \mu g m^{-3}$. Verma *et al.* (2015) showed that the large concentration of

PM in Lucknow was mainly resulted from the construction activity, industrial process and vehicular emission. Along with many commercial, industrial and vehicular activities, metro construction activity is also significantly contributing towards the PM concentration in the city.

TABLE 1

Monthly mean concentrations of PM_{2.5}, SO₂, NO₂ and NO at Lucknow in residential and industrial sites during 2015-2017

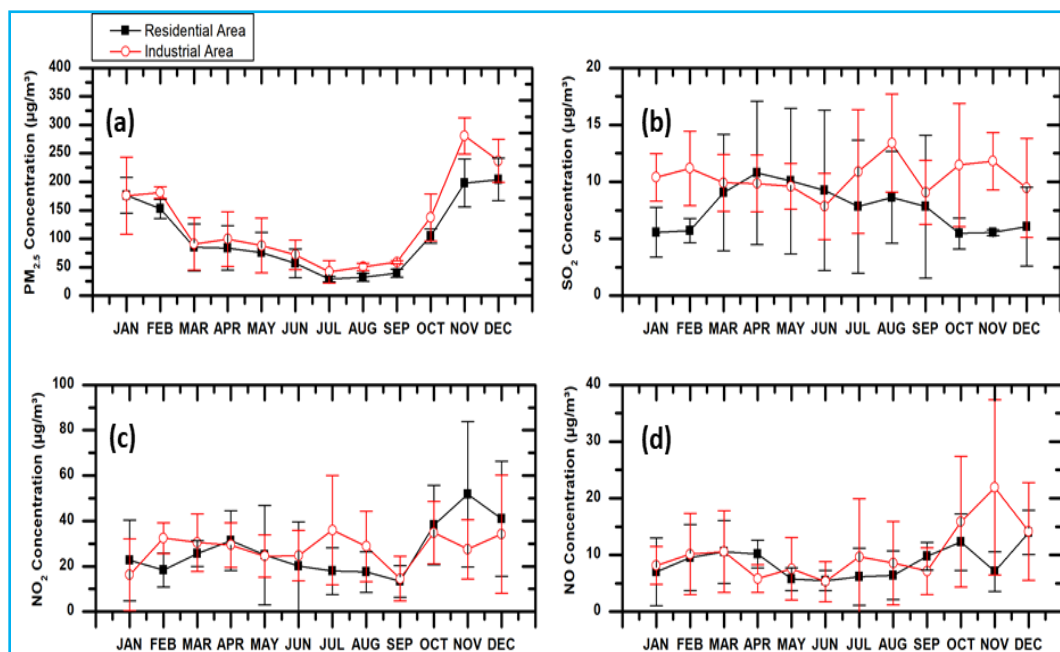
Months	PM _{2.5} (µg m ⁻³)		SO ₂ (µg m ⁻³)		NO ₂ (µg m ⁻³)		NO (µg m ⁻³)	
	Residential	Industrial	Residential	Industrial	Residential	Industrial	Residential	Industrial
January	176.7 ± 31.5	175.9 ± 67.8	5.6 ± 2.2	10.4 ± 2.9	22.6 ± 17.8	16.3 ± 15.9	7.0 ± 6.0	8.2 ± 3.3
February	152.4 ± 16.7	181.1 ± 10.1	5.7 ± 1.1	11.2 ± 3.3	18.4 ± 7.5	32.4 ± 6.8	9.5 ± 5.8	10.1 ± 7.1
March	84.8 ± 41.3	90.9 ± 46.0	9.1 ± 5.1	9.9 ± 2.5	25.6 ± 5.6	30.5 ± 12.8	10.5 ± 5.5	10.6 ± 7.2
April	83.6 ± 39.0	99.4 ± 47.8	10.8 ± 6.3	9.9 ± 2.5	31.3 ± 13.2	29.4 ± 9.8	10.2 ± 2.4	5.8 ± 2.4
May	75.8 ± 35.2	88.3 ± 47.9	10.1 ± 6.4	9.6 ± 2.0	25.0 ± 21.9	24.5 ± 9.4	5.7 ± 2.0	7.6 ± 5.5
June	56.6 ± 25.2	71.8 ± 25.9	9.3 ± 7.1	7.8 ± 3.0	20.1 ± 19.6	24.7 ± 11.1	5.5 ± 1.5	5.3 ± 3.5
July	29.5 ± 4.6	42.0 ± 19.8	7.8 ± 5.8	10.9 ± 5.4	17.9 ± 10.3	36.0 ± 24.1	6.2 ± 5.0	9.7 ± 10.3
August	32.3 ± 7.2	50.8 ± 6.4	8.6 ± 4.0	13.4 ± 4.3	17.5 ± 8.9	28.8 ± 15.5	6.4 ± 4.3	8.6 ± 7.3
September	39.6 ± 6.8	58.8 ± 3.1	7.8 ± 6.3	9.1 ± 2.8	13.4 ± 7.0	14.6 ± 9.8	9.7 ± 2.4	7.2 ± 4.2
October	104.8 ± 12.8	137.5 ± 41.2	5.5 ± 1.4	11.5 ± 5.4	38.2 ± 17.5	34.9 ± 13.8	12.3 ± 5.0	15.9 ± 11.5
November	198.0 ± 42.1	280.7 ± 31.8	5.5 ± 0.3	11.8 ± 2.5	51.8 ± 32.1	27.5 ± 13.1	7.1 ± 3.5	21.9 ± 15.4
December	204.3 ± 37.1	236.9 ± 37.5	6.1 ± 3.4	9.5 ± 4.4	41.0 ± 25.4	34.2 ± 26.0	14.0 ± 3.9	14.1 ± 8.6

The daily concentration of SO₂ at residential site varied from 0.4 and 34.9 µg m⁻³, with a mean of 7.6 ± 5.2 µg m⁻³ and at industrial site from 1.1 to 37.1 µg m⁻³, with a mean of 10.4 ± 5.4 µg m⁻³. Though the mean SO₂ was about 39% higher at the industrial site than the residential site, it was found to be lower than its 24-hour NAAQS value (80 µg m⁻³) at both the sites. This could be attributed to the use of low sulfur content fossil fuel, use of flue gas de-sulfurization for industrial processes and implementation of CNG vehicles. The daily mass concentration of NO₂ varied from 1.1 to 105.6 µg m⁻³, with mean value of 27.0 ± 21.2 µg m⁻³ at residential area over the entire time period whereas at industrial site, it varied from 1.1 to 81.4 µg m⁻³, with a mean of 28.1 ± 17.8 µg m⁻³. At residential site, about 3% of data sample of NO₂ was found to exceed to the corresponding NAAQS level (80 µg m⁻³), which was almost under the limit at industrial site. On the other hand, concentration of NO at residential site varied from 1.0 to 34.3 µg m⁻³ (mean: 8.7 ± 6.5 µg m⁻³) and at industrial site, it varied from 1.0 to 75.3 µg m⁻³ (mean: 10.3 ± 10.8 µg m⁻³). In a previous study, Verma *et al.* (2015) have also found lower mass concentrations of NO₂ and SO₂ than their NAAQS levels in Lucknow. In other studies, Nagpure *et al.* (2016) and Kishore *et al.* (2019) also observed lower mass concentration of SO₂ in Delhi, which lies north-western part of the IGB.

4.2. Monthly variability of air pollutants

Figs. 4(a-d) and Table 1 show monthly mean mass concentration of PM_{2.5}, SO₂, NO₂ and NO for residential

and industrial sites during the entire study period. All air pollutants show more or less similar monthly variations with highest concentration during the post-monsoon/winter season and lowest during the monsoon season, indicating that these air pollutants are released but they make different emission strength. The monthly mean concentrations of PM_{2.5} were highest in the post-monsoon and winter months at both residential and industrial sites, which are clearly depicted in Fig. 4 (a). Over all during the study period, the value of PM_{2.5}, SO₂, NO₂ and NO at industrial site was ~22%, ~36%, ~3% and 19% respectively higher than that of residential site. The higher value of PM_{2.5} indicates that the inflexible measures imposed on vehicular emission are inadequate in controlling the PM_{2.5} emissions (Biswas *et al.*, 2011). In another study at Lucknow, Verma *et al.* (2015) reported the PM₁₀ value about 216 µg m⁻³ and SO₂ and NO₂ about 25 and 35 µg m⁻³, respectively. According to these studies, the transport sector and construction activities are defined as the major contributors to the total loading of air pollutants. Rising of air pollution in Lucknow city to the existing levels can be attributed to the faster development. Values of SO₂ indicate that the concentrations at both the sites are below the national standard [Fig. 4(b)]. Industrial and vehicular emissions (mainly diesel vehicles) are the primary contributors of SO₂ in Lucknow. Monthly mean of SO₂ was found to be higher in the month of April (10.80 ± 6.30 µg m⁻³) at residential site; however, at industrial site, it was higher in August (13.40 ± 4.30 µg m⁻³). The mass concentration of SO₂ at industrial site was about 36% higher than the residential sites. Further, the mass concentration of NO₂ [Fig. 4(c)] at residential was



Figs. 4(a-d). Monthly mean plot for mass concentrations of (a) $PM_{2.5}$, (b) SO_2 , (c) NO_2 and (d) NO at the residential and industrial areas over the entire study period

TABLE 2

Seasonal mean concentration of $PM_{2.5}$, SO_2 , NO_2 and NO at Lucknow in residential and industrial sites during 2015-2017

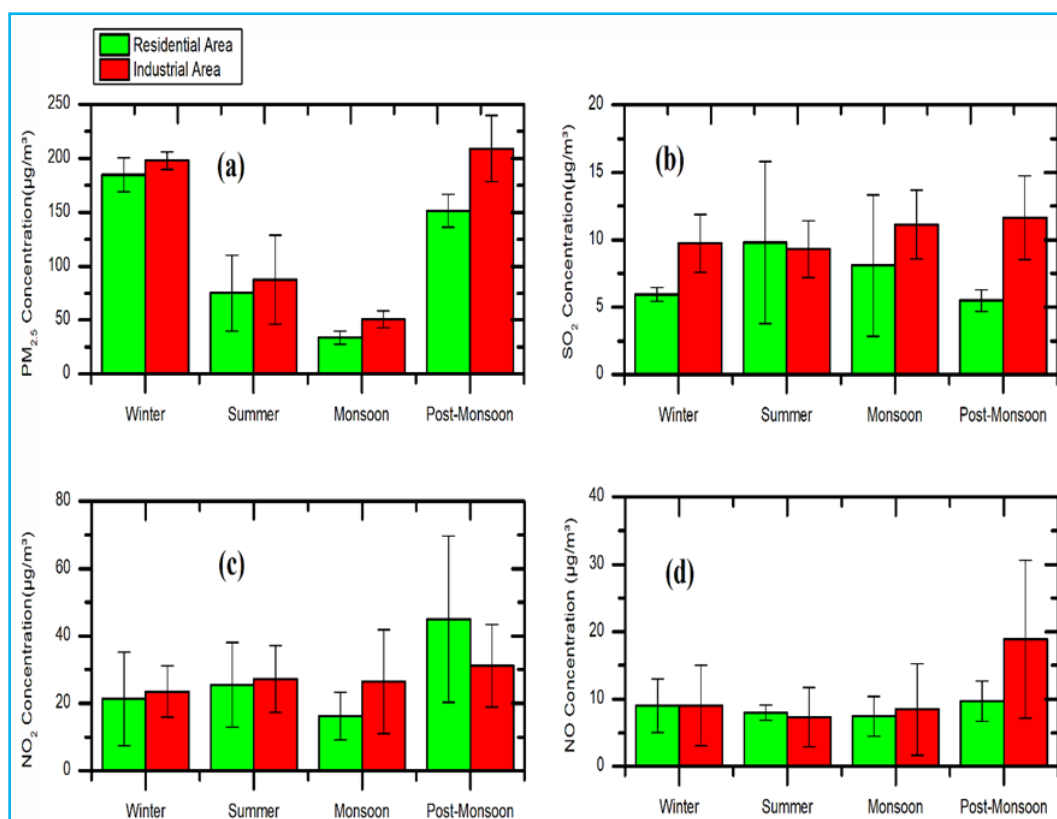
Season	$PM_{2.5}$ ($\mu g m^{-3}$)		SO_2 ($\mu g m^{-3}$)		NO_2 ($\mu g m^{-3}$)		NO ($\mu g m^{-3}$)	
	Residential	Industrial	Residential	Industrial	Residential	Industrial	Residential	Industrial
Winter	184.9 ± 15.8	197.8 ± 8.3	5.9 ± 0.5	9.7 ± 2.1	21.4 ± 13.9	23.5 ± 7.6	9.0 ± 4.0	9.1 ± 6.0
Summer	75.2 ± 35.2	87.6 ± 41.4	9.8 ± 9.0	9.3 ± 2.1	25.5 ± 12.5	27.2 ± 9.9	8.0 ± 1.1	7.3 ± 4.4
Monsoon	33.8 ± 6.0	50.5 ± 7.9	8.1 ± 5.2	11.1 ± 2.5	16.3 ± 7.1	26.5 ± 15.4	7.5 ± 2.9	8.5 ± 6.8
Post-Monsoon	151.4 ± 15.2	209.1 ± 30.6	5.5 ± 0.8	11.7 ± 3.1	45.0 ± 24.7	31.2 ± 12.3	9.7 ± 3.0	18.9 ± 11.7

higher in November ($51.78 \pm 32.09 \mu g m^{-3}$) whereas at industrial site, it was highest in the month of July ($35.98 \pm 13.83 \mu g m^{-3}$). Goods vehicles using diesel fuel are the main source of NO_2 emissions (Biswas *et al.*, 2011). SO_2 and NO_2 are important contributors towards secondary sulphate and nitrate formation through a series of complex reactions, which are the major components of fine particles. The mass concentration of NO [Fig. 4(d)] at residential site was highest in the month of December ($13.96 \pm 3.89 \mu g m^{-3}$) whereas at industrial site, it was higher in November ($21.93 \pm 15.43 \mu g m^{-3}$).

4.3. Seasonal variability of air pollutants

Seasonal mean variation of mass concentrations of $PM_{2.5}$, SO_2 , NO_2 and NO at the residential and industrial areas during the entire study period are shown in Fig. 5 and the values are given in Table 2. Seasonally, all the

measured air pollutants were found to be highest during the post-monsoon/winter season and lowest during the monsoon season almost at both the sites (residential and industrial). $PM_{2.5}$ mass concentrations were found to be higher by about 38% at the industrial site as compared to residential site [Fig. 5(a)]. In another study, Pandey *et al.* (2012) observed $PM_{2.5}$ mass concentration of $\sim 147 \mu g m^{-3}$ at residential site and $\sim 199 \mu g m^{-3}$ at industrial site in Lucknow during the post-monsoon/winter seasons in 2007-2008, which was found to be about 20% less at residential site and 4% less at industrial site as compared to the present study. Further, SO_2 mass concentrations were highest in summer ($9.8 \pm 6.0 \mu g m^{-3}$) at residential site and post-monsoon ($11.7 \pm 3.1 \mu g m^{-3}$) at industrial site whereas NO_2 was highest during the post-monsoon season at both the sites (residential: $45.0 \pm 24.7 \mu g m^{-3}$; industrial: $31.2 \pm 12.3 \mu g m^{-3}$). The mass concentration of NO_2 was found to be relatively higher at industrial site as



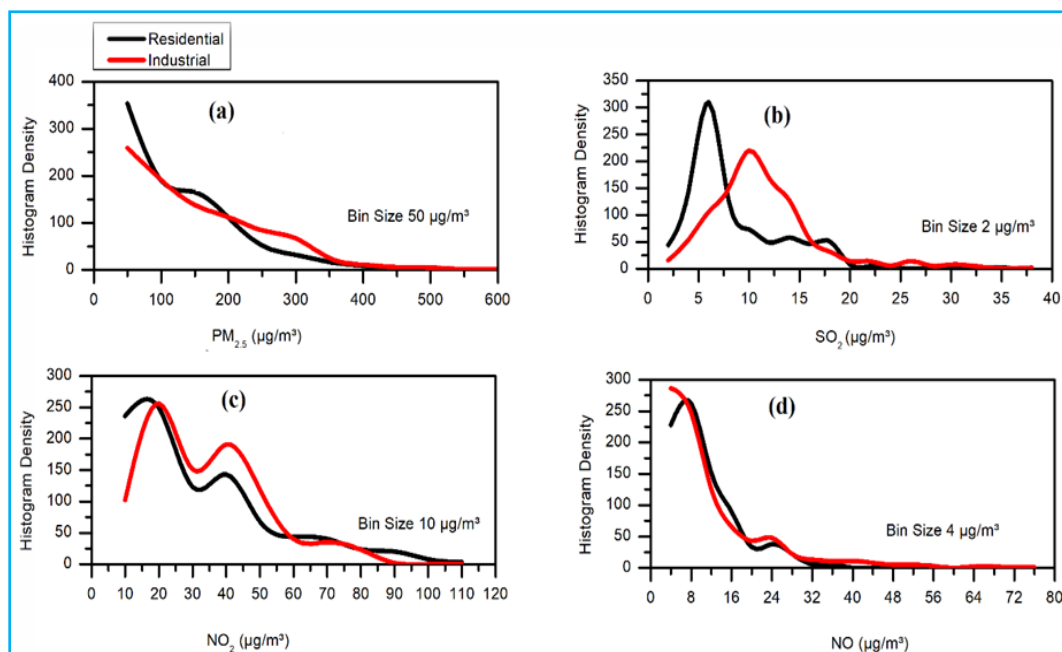
Figs. 5(a-d). Seasonal mean plot for mass concentrations of (a) PM_{2.5}, (b) SO₂, (c) NO₂ and (d) NO at the residential and industrial sites over the entire study period

compared to the residential site during all the seasons, except in post-monsoon, which indicates its major contribution from vehicular emissions at the industrial site. Though the mass concentration of NO was found to be higher at both the sites during the post-monsoon season [Fig. 5(d)], it is found to be ~94% higher at industrial site as compared to the residential site. At industrial site, the mass concentration of SO₂ was ~112% higher than that of residential site in post-monsoon season. However, NO₂ was ~31% lower at the industrial site as compared to the residential site in post-monsoon season.

The highest mass concentrations of air pollutants observed during the post-monsoon/winter season could be attributed to several factors such as enhanced emission sources due to trash/biomass residue burning during this time of the year and stable weather conditions with calm wind and shallow boundary layer height (Kulshreshtha *et al.*, 2009). In the post-monsoon/winter season, a substantial atmospheric condition restrains ventilation of near-surface air pollutants to free troposphere (Gaur *et al.*, 2014). A previous study at Lucknow also showed an intra-seasonal variability of PM_{2.5} mass concentration in 2007-2008 (Pandey *et al.*, 2012). They also observed highest PM_{2.5} concentrations during post-monsoon and winter

periods (~212 $\mu\text{g m}^{-3}$), which was about 4-5 times higher as compared to the concentrations observed in summer (~46 $\mu\text{g m}^{-3}$). Tiwari *et al.* (2013) have performed a study at Delhi (about 500 km away from Lucknow) during 2007-2009 and also observed the highest PM_{2.5} concentrations during the post-monsoon and winter periods (~150 $\mu\text{g m}^{-3}$).

Annual mean mass concentration variation of PM_{2.5} was found to be 80.1 ± 84.1 , 111.6 ± 67.9 and 103.9 ± 17.9 $\mu\text{g m}^{-3}$ at residential site and 85.2 ± 22.2 , 148.0 ± 32.7 and 129.7 ± 26.3 $\mu\text{g m}^{-3}$ at industrial site in the year 2015, 2016 and 2017, respectively. These values are about 2-3 times higher than its NAAQS (40 $\mu\text{g m}^{-3}$). On the other hand, annual mean NO₂ was about 15.5 ± 7.8 (15.5 ± 4.3), 33.7 ± 18.5 (30.5 ± 3.8) and 32.5 ± 20.2 (37.5 ± 4.4) and SO₂ about 12.1 ± 5.7 (8.1 ± 1.6), 6.7 ± 2.2 (10.7 ± 2.6) and 5.2 ± 1.3 (12.4 ± 1.6) $\mu\text{g m}^{-3}$ at residential (industrial) site during 2015, 2016 and 2017 respectively, which were found to be relatively lower than their NAAQS [NO₂ (40 $\mu\text{g m}^{-3}$) and SO₂ (50 $\mu\text{g m}^{-3}$)]. However, the annual mean of NO was found 8.4 ± 3.2 (3.5 ± 1.6), 6.3 ± 2.2 (11.0 ± 3.4) and 11.2 ± 2.3 (16.6 ± 4.7) $\mu\text{g m}^{-3}$ at residential (industrial) site during 2015, 2016 and 2017 respectively.



Figs. 6(a-d). Histogram density plots for (a) $PM_{2.5}$, (b) SO_2 , (c) NO_2 and (d) NO at the residential and industrial sites over the entire study period

4.4. Frequency distribution of air pollutants

Figs. 6(a-d) shows histogram density plots for daily $PM_{2.5}$, SO_2 , NO_2 and NO at residential and industrial sites over the entire study period. For $PM_{2.5}$ [Fig. 6(a)], about 58% (50%), 29% (27%), 9% (16%) and 3% (5%) of data points lie in the range of 0-100, 200-300, 300-400 and above 400 $\mu g m^{-3}$ respectively at residential (industrial) sites whereas for SO_2 [Fig. 6(b)], about 22% (39%) data values lie between 10 and 20 $\mu g m^{-3}$, with about 75% (54%) of data points less than 10 $\mu g m^{-3}$ at residential (industrial) sites. On the other hand, for NO_2 [Fig. 6(c)], about 51% (38%), 27% (36%), 16% (21%) and 6% (3%) of data points lie in the range 0-20, 20-40, 40-70 and above than 70 $\mu g m^{-3}$ respectively at residential (industrial) site. However, for NO [Fig. 6(d)], about 58% (59%), 32% (26%) and 8% (14%) data points lie in range 0-8, 8-20 and greater than 20 $\mu g m^{-3}$ respectively at residential (industrial) site.

4.5. Source identification for air pollutants

Air mass back-trajectory analyses were performed using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2010) to identify the probable source sectors of measured air pollutants over the station (Lucknow). The back-trajectory analyses were carried out at the height of 1000 m above ground level and for 120-hours back duration during the study period from January 2015 to December 2017.

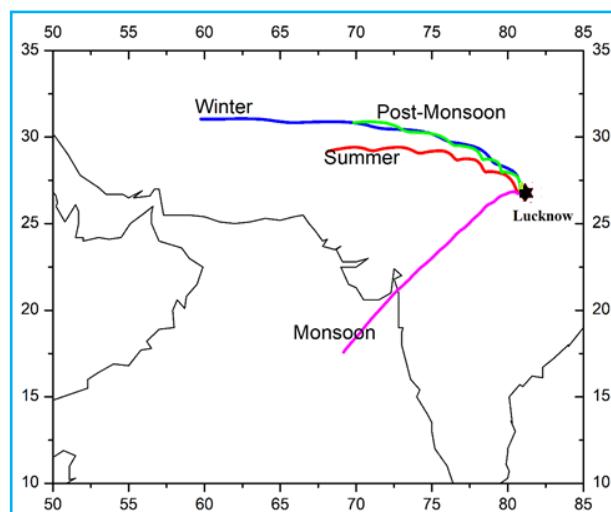


Fig. 7. HYSPLIT calculated 5-day air mass backward trajectory clusters at Lucknow for the entire study period

Gridded wind field data from the Global Data Assimilation System (GDAS) was used with a spatial resolution of $1^\circ \times 1^\circ$ and a time resolution of 1 hour (Kanamitsu, 1989). Fig. 7 shows four different air mass trajectory cluster over the study period only for those seasons when measurements were available. The air masses were found to be coming over the station mostly from the north-northwest (N-NW) direction during all the seasons, except in monsoon, when air masses were from

the south-west direction. In summer season, dusts from the adjacent desert regions were the main source of pollution over the station. Long-range air masses were detected from the contiguous regions of Afghanistan and Pakistan (Fig. 7), which bring polluted air to the receptor site (Mukherjee and Agrawal, 2017). Post-monsoon and winter seasons showed the uni-directional movement of polluted air masses for the most part of north-west direction, with relatively long-range transport in winter. Results are highly associated with the observed higher PM mass concentration over the station during these seasons, as shown in Table 2. During the period, entire north-west regions are the huge source of agricultural biomass burning emissions (Kaskaoutis *et al.*, 2014; Sharma *et al.*, 2017; Kanawade *et al.*, 2020), which may also cause higher PM concentrations in Lucknow apart from the impact from local emissions.

5. Conclusions

Simultaneous measurements of various criteria pollutants such as NO₂, SO₂, NO and PM_{2.5} were carried out at two contrasting locations over an urban station Lucknow, in the central IGB during the period from January 2015 to December 2017. The major findings of the present study are as follows:

(i) The mean mass concentration of PM_{2.5}, SO₂, NO₂ and NO was observed to be 102.0 ± 80.5 , 7.6 ± 5.2 , 26.96 ± 21.19 and 8.6 ± 6.5 $\mu\text{g m}^{-3}$ at residential site and 128.0 ± 98.9 , 10.4 ± 5.4 , 28.2 ± 17.4 and 10.4 ± 10.8 $\mu\text{g m}^{-3}$ at industrial site.

(ii) The mean mass concentrations of PM_{2.5} and NO₂ were found to be higher by ~58% and 5% at residential site and ~67% and 1% at industrial site compared to their prescribed NAAQS levels, respectively. However, SO₂ never exceeded to its NAAQS at both the sites.

(iii) The mass concentration of NO₂ was ~31% less at industrial site than that of residential site; however, SO₂, NO and PM_{2.5} was ~112%, ~94% and ~38%, respectively higher at industrial site than the residential site during the post-monsoon season.

(iv) The seasonal mean mass concentrations of PM_{2.5}, SO₂, NO₂ and NO were found highest in winter/post-monsoon season at both the sites (residential and industrial site), which were largely associated with the air mass back-trajectories from N-NW direction.

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