Variation of ambient air pollutants concentration over Lucknow city, trajectories and dispersion analysis using HYSPLIT4.0

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Abstract. The present study deals with the analysis of daily average concentrations of respirable suspended particulate matter (RSPM- PM10), sulfur dioxide (SO2), and nitrogen dioxide (NO2) at seven monitoring stations namely, Hazratganj, Talkatora, Mahanagar, Aliganj, Sarai Mali Khan, Gomtinagar, and Ansal TC in Lucknow city from 2016 to 2020. The analysis shows that the annual average concentration of RSPM varies from 148.74 to 323.05 \( \mu g/m^3 \), SO2 varies from 7.11 to 8.94 \( \mu g/m^3 \) and NO2 from 23.52 to 31.86 \( \mu g/m^3 \) at all the locations. From the analysis of seasonal variation, it is found that the minimum concentration of RSPM found to be 81.59 \( \mu g/m^3 \) in monsoon and maximum concentration was found to be 447.47 \( \mu g/m^3 \) in post-monsoon. However, the seasonal variation of SO2 was found in the range of 5.55 to 10.94 \( \mu g/m^3 \) and NO2 in the range of 20.23 to 38.40 \( \mu g/m^3 \), which are below the prescribed standards. The pollution level decreased to some extent due to the COVID-19 lockdown in the year 2020 but not below the prescribed standard for RSPM. The levels of PM10 in Lucknow are not reducing despite the government of India banning industries and adopting other safeguards within the city. The Trajectory and Dispersion study using the HYSPLIT4.0 model shows insufficient local pollution control, and pollutants are carried from adjacent locations due to the wind blowing from north-west direction to keep daily pollution levels over the standards prescribed by Central Pollution Control Board (i.e., 100 \( \mu g/m^3 \)). The peak concentration of RSPM is recorded to be 323.05 \( \mu g/m^3 \) for the year 2017 at the Hazratganj monitoring station. Over the study region, wavelet analysis of monthly averaged values of PM10 data sets at all seven stations revealed that the presence of semi-annual and annual periodicity. The findings reveal that controlling of particulate matter pollution in the city is a significant concern and has an alarming situation as compared to SO2 and NO2 pollutants.

Keywords. Nitrogen dioxide (NO2); sulfur dioxide (SO2); respirable suspended particulate matter (RSPM/PM10); wavelet; HYSPLIT4.0.

1. Introduction

Air pollution is the presence of various gases, foreign particles, and contaminants in the atmosphere at levels high enough to harm human health and aggravate various respiratory ailments in living creatures. Nitrogen dioxide (NO2), sulfur dioxide (SO2), respirable suspended particulate matter (RSPM/PM10), and suspended particulate matter (SPM) are the principal pollutants that impact human health, climate change, and the environment [1]. Vehicle emissions are the primary source of pollution in the environment, as they contain a variety of pollutant gases such as nitrogen oxides, sulfur oxides, carbon dioxide, carbon monoxide, PM10, and PM2.5. Due to traffic pollution, industrialization, population growth, and other factors, these pollutants’ concentration increase daily [2, 3]. With the increasing population, the need for vehicles also increases [4, 5], and as the need/demand for vehicles increases, the amount of pollution emitted by these vehicles also increases [6]. These pollutants data were collected and monitored using methods like the west and gaeke method for SO2, Jacob and Hochheiser method for NO2, and the gravimetric technique used for the particulate matter PM10. The design manual for roads and bridges (DMRB) model was used to predict concentration, and the trends of pollutants were analysed to study the environmental effects [7]. The modelling phase uses several modelling techniques such as artificial neural network (ANN), Kriging, and many others to determine the optimum values for parameters using various methods [8, 9].

As a result, air pollution causes many health risks, which could be mixture of other contaminants of varying composition rather than a single pollutant [10–12]. One of these pollutants is particulate matter, which generates from...
numerous indoor, and vehicular activities causes diseases such as autoimmune, cardiovascular [13], respiratory, neoplastic, etc, [14]. The other pollutants which affect the environment and human health are NO₂, generated from the combustion of fuels, i.e. petrol and diesel in automobiles. The combustion of these fuels releases tiny particulate matter size <10 μm, which could also cause harmful diseases to humans [15].

Meteorological parameters such as wind speed, temperature, humidity, and solar radiation affect the atmospheric quality [16–18]. Rainfall helps to reduce the pollution level as rain droplets settle the particulate matter along with them [19]. It is reported that PM₂.₅ pollution is responsible for 0.8 million premature deaths and 6.4 million of life lost per year worldwide [20]. A particulate matter sample could also contain Magnetic minerals, with bulk iron content ranging from 5 to 15 % of urban atmospheric PM, with iron oxides and hydroxides accounting for 10 - 70 % of the bulk iron content. Magnetite was the most common mineral in particulate matter [21]. The prediction could be made based on historical data, normalized with the meteorological parameters, and then future concentrations of pollutants predicted with the help of Artificial Neural Networks (ANN) [22]. Considering all these facts, the Government of India has taken strict actions to reduce pollution in the past decades. Some of them are (i) natural gas as a fuel for production processes, (ii) Continuous monitoring of currently operating coal using industries close to the city boundary and disapproval of new coal using industries inside the city limits, and (iii) closing every brick factory within 20 kilometres of Lucknow City, (iv) using low-sulfur diesel and installing scrubbers on diesel-powered vehicles [23].

Seasonal variation of the particulate matter composition in agreement with the air trajectories was observed in eastern India [24]. High concentrations are sometimes due to transport from sources, as was detected in North America [25], South America [26], Asia [27–29], the Middle East [30], Africa [31], Australia [32], and Europe [33]. Regarding the Indian context, the studies are considered and presented in table 1.

The present study is carried out to see the variation of pollutants concentration over Lucknow city for five years (2016-2020). Lucknow is the capital of Uttar Pradesh, the most populated state of India. There is heavy traffic of vehicles, many industries near the city, and many government offices in the city. It is rapidly growing in mid-sized cities in the developing world with air pollution issues and economic limitations (e.g., poor quality fuel). Under the National Air Quality Monitoring Programme (NAMP) of the Central Pollution Control Board (CPCB), the concentration of SO₂, NO₂ and RSPM is being monitored at seven stations in Lucknow. The data for five years from 2016 to 2020 has been utilised for analysis in the present study. The wind rose diagram has also been plotted for the wind direction and speed observed in Lucknow city.

### Table 1. Different studies observed related to the pollutants concentration over India.

| Study Area | Pollutants type | Techniques used | Key observation |
|------------|-----------------|-----------------|----------------|
| Five Indian rural sites | PM₉₀, SO₂, NO₂ | Temporal variation and correlation | Increment of AOD due to the urbanisation and transportation |
| Nagpur | PM₉₀, SO₂, NO₂ | CHAID Decision tree, 3D visualisation | Conc. is more influenced by the location and meteorology then the height from the surface |
| Karunya Nagar (Tamil Nadu) | PM₉₀, PM₂.₅, PM₁₀, CO₂, formaldehyde | Statistical Techniques | Conc. is more influenced by the location and meteorology then the height from the surface |
| Delhi, Lucknow, Nagpur, Kanpur, Chennai, Bhopal, Jamshedpur (East India) | PM₂.₅, Black carbon, PM₂.₅ | Back trajectories, daily variation | BC increases with the PM₂.₅ conc. |
| Lucknow | PM₂.₅, CO₂, CO | Annual variation and correlation | Emission were within the permissible limits |
to predict the effect of wind speed and direction on the concentration of pollutants. Seasonal variation in the concentration of pollutants has also been studied using the five years data from all seven monitoring stations. The Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT) model was developed by National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratory (ARL) and the Australian Bureau of Meteorology Research Centre in 1998 [40], which was used for trajectories and air pollution dispersion analysis [41–47] in the present study at Lucknow city. This is necessary to analyse the pattern of dispersion of pollutants concentration.

Furthermore, wavelet analysis in MATLAB has been applied to crosscheck the periodicity of the data for respirable suspended particulate matter. It has been used to explore if any periodicity exists in the variation of RSPM. Knowing the maximum effect of RSPM in the long term, in which season or month a concerned pollutant could affect the environment more periodically, is necessary. There could be the limitation of this work as of the lockdown phase affects the pollution concentration over the city. From the literature presented above, it is found that no study has been reported in the past on HYSPLIT4.0 and Wavelet analysis on Lucknow city, which can correlate the effect of wind direction and the concentration due the farthest industries in Delhi or the desert in the Rajasthan, could increase the level of pollution.

2. Material and methodology

2.1 Study area

Lucknow (26.84° N, 80.94° E) is the capital and largest city of Uttar Pradesh. It is the third-largest city in the north, east, and central India after Delhi and Kolkata, and the second-largest city in the north and central India after New Delhi. Lucknow, popularly known as the city of Nawabs, is situated at an elevation of approximately 123 meters above sea level and covers an area of 2,528 square kilometres. It is located in the middle of the Indus-Gangetic Plain and comes in a seismic zone. The primary geographical feature is the Gomti River which divides it into the trans-Gomti and Cis-Gomti regions. Lucknow has a humid subtropical climate with cool dry winters from mid-November to February, and dry hot summers from late March to June. The rainy season is from July to mid-September. In the present study, a year has been divided into four different seasons, i.e., summer (March to May), monsoon (June to September), post-monsoon (October to November), and winter (December to February). The city population is dense, with 1,815 inhabitants/km² according to the census 2011. Major cities surrounding Lucknow are Kanpur (spatial distance ~ 90 km) in the south-west direction, Farukhabad (spatial distance ~ 138 km) in the south-east, Barabanki (spatial distance ~ 29 km) in the east, Unnao (spatial distance ~ 54 km) in the west, Raebareli (spatial distance ~ 75 km) in the south, and Sitapur (spatial distance ~ 115) in the north.

Uttar Pradesh Pollution Control Board (UPPCB) has seven monitoring stations in the city. All of them are manually operated monitoring stations, namely: Hazratganj (26.85° N, 80.94° E), Mahanagar (26.87° N, 80.95° E), Aliganj (26.89° N, 80.94° E), Sarai Mali Khan (26.86° N, 80.90° E), Ansal TC (26.79° N, 81.00° E), Gomtinagar (26.84° N, 81.00° E), and Talkatora (26.83° N, 80.89° E). In addition, an industrial area named Talkatora contributes to air pollution. However, Hazratganj is the most populous area of the city, contributing to the growth in pollutant concentration. All the monitoring stations are shown in figure 1.

The data used in the present study, including RSPM, SO2, and NO2, were obtained from the UPPCB website [48], and meteorological parameters were obtained from the Indian Meteorological Department [49].

2.2 Monitoring programme

The daily average concentration of RSPM (particle size less than 10 μm), SO2, and NO2 at all seven monitoring stations are monitored under SAMP (State ambient air monitoring program) governed by CPCB (Central Pollution Control Board). A Respirable dust sampler (RDS) is used to collect the samples. The sampling frequency is twice a week, such that a minimum of 104 samples should contain at one site in a year. The collected samples are used for further analysis of various pollutants using standard methods prescribed by Central Pollution Control Board (CPCB) [23].

Particulate matter RSPM is estimated gravimetrically. A known amount of air passes through a glass fibre filter at a flow rate of 0.8-1.3 m³/min on eight hourly basis for 24 hours. The high volume sampler (HVS) consists of a protective casing, a blower, a voltage stabilizer, a time totalizer, a rotameter, and a filter holder capable of supporting a 20.3 x 25.4 cm Glass Fibre Filter, the cyclone that uses centrifugal force to remove dust is used for sampling of the pollutants. A particle in a rotating air stream is subjected to a centrifugal force that accelerates it towards a surface where it will influence and lose momentum, thus being removed from the air stream. In a typical cyclone pre-collector, the air enters tangentially at its side and swirls around inside. Particles above 10 μm are thrown to the cyclone walls and collected at its base (“grit-pot”). The air containing respirable dust was left through the central exit at the top of the cyclone and collected on the filter paper. The flow rate used for collecting the sample is 1.1 m³/min. The concentration of particulate matter gravimetrically is determined as follows [50]:
\[
C_{PM_{10}} = \frac{(W_f - W_i)}{V} \times 10^6
\]

where, \(C_{PM_{10}}\) – Concentration of RSPM or PM\(_{10}\), in \(\mu g/m^3\); \(W_i\) – initial weight of filter, in gm; \(W_f\) – final weight of filter, in gm; \(V\) – Volume of air sampled, in \(m^3\).

Gaseous pollutants, namely \(SO_2\) and \(NO_2\), are collected on a four-hourly basis for 24 hours by drawing air at the flow rate of 1 L/min and analyzed by West and Gaekke, and Jacob and Hochheiser method, respectively [51–53]. In addition, wind data was used to plot the Wind Rose diagram to get the wind direction and speed over the Lucknow city throughout the study period.

2.3 **HYSPLIT4.0 (Hybrid Single-Particle Lagrangian Integrated Trajectory model)**

The National Center for Environment Prediction (NCEP)/National Center for Atmospheric Research (NCAR), Global Data Assimilation System (GDAS 1°) data and the HYSPLIT4.0 model June 2015 release, were used to perform back trajectory and dispersion analysis [40]. GDAS 0.5° data is missing vertical velocity, and it was recently found by SU et al [45] that GDAS 1° data is better in computing back trajectory compared to data GDAS 0.5°. Therefore, GDAS 1° data has been used solely. The following is a summary of this model configuration for trajectory runs: Input data: GDAS 1° data, model version: HYSPLIT4.0 model June 2015 release [54–56], time to run: 48 hours for each 6-hour interval. There are no set bounds in the model domain. Trajectories can travel as far as possible in the global domain; trajectory computation method: isentropic trajectories; model altitude for trajectory calculation: 500 meters above ground level (AGL); and model top for trajectory computations: ten thousand meters above ground level (AGL).

In this study, GDAS 1° data has also been used for dispersion runs. The model was permitted to use a 0.1 cm/s deposition rate, with a release top of 50 m AGL and a release bottom of 0 m AGL. It assumes that a unit mass releases for 1 hour at 12 UTC of the day and estimated 24-hour backward dispersion with a 6-hour averaging time and a top of the averaged layer at 100 m AGL. The online version of HYSPLIT4.0 for trajectory and dispersion studies has been used [57] for the present study.

2.4 **Trajectories**

Several trajectory models are constructed for the analysis of atmospheric movement. They can examine how the air moves forward and backward in time. The NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4.0) model has been used in this study. This model is accessible online (http://www.arl.noaa.gov/HYSPLIT_info.php). Throughout the sampling interval, the model was utilized to determine the position of the air sampled backward from the receptor site at various starting times. The HYSPLIT4.0 model was used to perform back trajectory analysis over Lucknow city for four seasons to investigate the aerosol paths from multiple sources 500 meters above ground level [40]. In the study of long-term transport of aerosols from different locations, at 6-hour intervals (i.e.,
48-hour mass isentropic back trajectories in Lucknow city were estimated. The permissible value for RSPM suggested by the Central Pollution Control Board for a clean environment is 100 \( \mu g/m^3 \).

### 2.5 Wavelet analysis for periodicity

It is a tool for signal processing used to assess dominant modes within a time series by decomposing them into time-frequency domains [58]. The wavelet scalogram has been used to determine periodicity in pollutant concentration with time-series data and detect dominant periods [59, 60]. The approach in the present study used a monthly averaged data set with the help of Morlet Mother Wavelet, normalized by standard deviation. Morlet wavelet explains as a plane wave modulated by Gaussian for a wavelet function \( \Psi_0(\eta) \) depending on non-dimensional time parameter \( \eta \).

\[
\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}
\]  

Where \( \omega_0 \) is the non-dimensional frequency [58], for this study, wavelet power spectrum using Morlet wavelet for Gaussian white noise with standard deviation normalization has been used [58].

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**Table 2.** Annual Average Concentration (\( \mu g/m^3 \)) of pollutants PM\(_{10}\), SO\(_2\) and NO\(_2\) at all seven monitoring Stations (i.e. Commercial, Residential, and Industrial area).

| STATION                        | PM\(_{10}\)  | SO\(_2\)  | NO\(_2\)  | PM\(_{10}\)  | SO\(_2\)  | NO\(_2\)  | PM\(_{10}\)  | SO\(_2\)  | NO\(_2\)  | PM\(_{10}\)  | SO\(_2\)  | NO\(_2\)  | PM\(_{10}\)  | SO\(_2\)  | NO\(_2\)  |
|-------------------------------|-------------|---------|----------|-------------|---------|----------|-------------|---------|----------|-------------|---------|----------|-------------|---------|----------|
| HAZRATGANJ (COMMERCIAL)       | 217.68      | 7.77    | 26.91    | 216.33      | 7.98    | 27.50    | 214.50      | 7.42    | 26.82    | 198.13      | 7.54    | 26.91    | 216.59      | 7.92    | 27.38    |
| SARAI MALI KHAN (COMMERCIAL)  | 323.05      | 8.33    | 26.81    | 243.25      | 8.70    | 26.28    | 233.55      | 8.11    | 25.22    | 212.06      | 8.15    | 25.26    | 214.07      | 8.52    | 27.04    |
| ANSAL T.C. (COMMERCIAL)       | 244.95      | 8.39    | 30.16    | 230.86      | 8.53    | 29.30    | 218.26      | 7.63    | 28.27    | 204.50      | 8.15    | 28.87    | 229.43      | 7.26    | 30.59    |
| GOMTI NAGAR (COMMERCIAL)      | 197.76      | 8.61    | 30.95    | 216.38      | 8.94    | 31.86    | 190.02      | 8.40    | 29.59    | 169.28      | 8.14    | 30.32    | 224.60      | 8.71    | 31.16    |
| MAHANAGAR (RESIDENTIAL)       | 211.21      | 7.77    | 33.42    | 163.56      | 7.55    | 30.73    | 158.96      | 7.11    | 30.68    | 189.26      | 7.58    | 31.61    | 148.74      | 7.22    | 33.46    |
| ALIGANJ (RESIDENTIAL)         | 211.87      | 7.48    | 28.63    | 174.75      | 7.63    | 30.12    | 174.75      | 7.71    | 30.17    | 224.60      | 7.62    | 30.68    | 221.73      | 7.95    | 33.46    |
| TALKATORA (INDUSTRIAL)        | 244.95      | 8.61    | 30.95    | 216.38      | 8.94    | 31.86    | 190.02      | 8.40    | 29.59    | 169.28      | 8.14    | 30.32    | 224.60      | 8.71    | 31.16    |

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00, 06, 12, and 18 UTC every day), 48-hour mass isentropic back trajectories in Lucknow city were estimated. The approach in the present study used a monthly averaged data set with the help of Morlet Mother Wavelet, normalized by standard deviation. Morlet wavelet explains as a plane wave modulated by Gaussian for a wavelet function \( \Psi_0(\eta) \) depending on non-dimensional time parameter \( \eta \).

\[
\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}
\]  

Where \( \omega_0 \) is the non-dimensional frequency [58], for this study, wavelet power spectrum using Morlet wavelet for Gaussian white noise with standard deviation normalization has been used [58].
3. Results and discussion

Variations of average concentrations with PM$_{10}$, SO$_2$, and NO$_2$ are studied and discussed in the following sections:

3.1 Annual average concentration

The annual average concentration of PM$_{10}$ over Lucknow city is shown in figure 2(a). It shows considerable variation at all the monitoring stations from 2016 to 2020. The highest annual average concentration among all the stations was observed at Hazratganj (323.05 µg/m$^3$) station in 2017 because Hazratganj, a commercial area, has a significant traffic issue and is highly populated. On the other hand, Ansal TC showed fluctuating variation in concentration for the entire study period, possibly because of the institutional vacations for some days in the year. Sarai Mali Khan (commercial) and Gomtinagar (commercial) showed a gradual increase till 2017, with a peak concentration of 243.25 µg/m$^3$ and 233.55 µg/m$^3$ in 2017, respectively and then a gradual decrease of 163.56 µg/m$^3$ and 158.96 µg/m$^3$ respectively till 2020, because of Covid lockdown, various anthropogenic activities were closed in the year 2020. Mahanagar and Aliganj, the residential areas, show a minimum concentration of 153.52 µg/m$^3$ and 118.34 µg/m$^3$ in 2020, respectively. These concentrations also decreased because of less anthropogenic activities and vehicle movements around the area due to the implication of lockdown due to the COVID-19 pandemic.

The annual average concentration of SO$_2$ was observed [figure 2(b)] to be maximum for Talkatora (industrial) and Sarai Mali Khan (commercial) stations for the entire study period. It may be because of excessive burning of fossil fuels, i.e. coal and oil, in the region. Talkatora (industrial) station shows the maximum concentration in 2017 (8.85 µg/m$^3$), and Ansal TC (commercial) has a minimum concentration (7.11 µg/m$^3$) in 2020 because the institutional area was closed in the Covid lockdown. Residential areas like Mahanagar and Aliganj also show

Figure 3. Seasonal Variation (winter, summer, monsoon, and post monsoon) graphs of PM$_{10}$ at all monitoring stations for study period 2016-2020.
a considerable concentration of SO₂ compared to other commercial areas because the maximum population resides in this area compared to the other areas. Annual variation of NO₂ shows [figure 2(c)] a sudden rise in concentration after 2017, which kept on increasing until 2020. Hazratganj (commercial) and Talkatora (industrial) stations account for maximum concentrations because of the maximum traffic congestion in those areas, whereas Aliganj shows a minimum spike in concentration. Sarai Mali Khan, Gomtinagar, and Ansal TC, the commercial areas, show an average spike in NO₂ concentration. The annual average concentration of pollutants PM₁₀, SO₂ and NO₂ at all seven monitoring Stations is given in table 2.

### 3.2 Seasonal variation

Seasonal variation in concentration of the pollutants has been analysed at all seven monitoring stations. The seasons considered are Winter (December-February), Summer (March-May), Monsoon (June to September), and Post-Monsoon (October - November).

#### 3.2.1 PM₁₀ variation

Seasonal variation of PM₁₀ concentration (µg/m³) is depicted in figure 3 and table 3, showing visible fluctuations for the study period. At Hazratganj station figure 3(a), PM₁₀ concentration is highest in post-monsoon, followed by winter, summer, and monsoon. The maximum concentration for post-monsoon was 447.46 µg/m³ in 2017, and the minimum was 114.30 µg/m³ for the monsoon of 2016, which is above the standard prescribed by the Central Pollution Control Board (100 µg/m³). Similarly, at Sarai Mali Khan, Gomtinagar, and Talkatora [figures 3(b),(d),(g)], winter and post-monsoon values are almost higher as compared to the other two seasons. At Ansal TC figure 3(c), PM₁₀ concentration was exceptionally high (271.66 µg/m³) for the summer of 2019. Mahanagar and Aliganj [figures 3(e), (f)] have a maximum concentration of 286.70 µg/m³ and

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| SEASONS   | STATIONS       | 2016   | 2017   | 2018   | 2019   | 2020   |
|-----------|----------------|--------|--------|--------|--------|--------|
| WINTER    | HAZRATGANJ     | 287.07 | 376.27 | 342.21 | 212.71 | 268.81 |
|           | SARAI MALI KHAN| 293.20 | 279.39 | 330.48 | 247.54 | 259.85 |
|           | ANSAL T.C.     | 276.37 | 247.47 | 259.66 | 208.66 | 258.83 |
|           | GOMTINAGAR     | 285.17 | 321.08 | 315.78 | 267.03 | 253.50 |
|           | MAHANAGAR      | 286.70 | 250.81 | 226.10 | 216.66 | 246.60 |
|           | ALIGANJ        | 305.67 | 294.47 | 258.18 | 198.87 | 189.43 |
|           | TALKATORA      | 276.07 | 268.09 | 337.43 | 275.31 | 287.89 |
| SUMMER    | HAZRATGANJ     | 219.60 | 307.70 | 240.66 | 249.06 | 178.73 |
|           | SARAI MALI KHAN| 242.77 | 300.53 | 219.07 | 243.93 | 126.86 |
|           | ANSAL T.C.     | 238.70 | 236.87 | 208.20 | 271.69 | 147.38 |
|           | GOMTINAGAR     | 231.40 | 255.63 | 221.81 | 223.37 | 104.54 |
|           | MAHANAGAR      | 213.13 | 283.63 | 207.44 | 192.80 | 146.73 |
|           | ALIGANJ        | 256.13 | 207.10 | 185.66 | 183.60 | 121.80 |
|           | TALKATORA      | 253.60 | 231.83 | 255.75 | 295.94 | 211.42 |
| MONSOON   | HAZRATGANJ     | 114.35 | 232.45 | 181.40 | 161.97 | 119.66 |
|           | SARAI MALI KHAN| 106.00 | 137.37 | 156.05 | 170.96 | 81.59  |
|           | ANSAL T.C.     | 97.75  | 105.24 | 151.86 | 124.53 | 83.80  |
|           | GOMTINAGAR     | 88.83  | 118.91 | 128.17 | 89.58  | 85.47  |
|           | MAHANAGAR      | 99.03  | 117.42 | 163.64 | 119.55 | 119.69 |
|           | ALIGANJ        | 84.38  | 96.75  | 93.59  | 127.73 | 98.00  |
|           | TALKATORA      | 110.18 | 133.07 | 128.32 | 165.29 | 138.17 |
| POST MONSOON| HAZRATGANJ   | 317.35 | 447.47 | 232.60 | 169.95 | 329.55 |
|           | SARAI MALI KHAN| 282.05 | 314.89 | 248.76 | 219.13 | 219.75 |
|           | ANSAL T.C.     | 256.70 | 245.58 | 247.56 | 236.97 | 213.15 |
|           | GOMTINAGAR     | 330.00 | 298.42 | 246.86 | 225.37 | 218.55 |
|           | MAHANAGAR      | 240.95 | 235.86 | 249.40 | 162.39 | 284.90 |
|           | ALIGANJ        | 259.75 | 249.81 | 195.43 | 219.31 | 216.15 |
|           | TALKATORA      | 284.70 | 268.37 | 230.18 | 160.15 | 299.95 |
305.66 µg/m³ respectively for the winter of 2016 and a minimum concentration of 99.025 µg/m³ and 84.37 µg/m³, respectively for the monsoon of 2016. High values during the post-monsoon and winter season might be attributed to the locally emitted and transported pollutants and stable conditions persisting over the area during that period. In addition, there may be a temperature inversion over the region, which will further help enhance the pollutants leading to high concentration over the study area. The lowest concentration during the monsoon period is due to rainfall, leading to the washout of pollutants over the region.

3.2.2 SO₂ variation The seasonal variation of SO₂ is depicted in figure 4 and shown in table 4, indicating that the concentration is below the prescribed limits given by the central pollution control board which is 80 µg/m³ and demonstrated by the horizontal lines in figure 4. Stations Hazratganj [figure 4(a)] and [figure 4(b)] Sarai Mali Khan show a spike in concentration for the year 2017 during the post-monsoon season (i.e., 10.92 µg/m³ and 10.97 µg/m³ respectively). In contrast, Ansal TC [figure 4(c)] has a peak concentration of 11.40 µg/m³ during post-monsoon of 2019, and Gomtinagar [figure 4(d)] shows a maximum concentration of 10.09 µg/m³ during the winter of 2016. Both Mahanagar [figure 4(e)] and Aliganj [figure 4(f)] have their maximum SO₂ concentration of 10.09 µg/m³ and 10.84 µg/m³ during the winter of 2016 but have a lesser concentration compared to other stations. Talkatora [figure 4(g)] had a maximum peak of 11.06 µg/m³ in the post-monsoon of 2017. The higher value of SO₂ concentration in the post-monsoon and some of the winter seasons may be because of the use of biomass as a domestic fuel in the city. The biomass burning in the city to combat the chilling cold around the city also leads to significantly higher SO₂ at night. As in the commercial area, the value of SO₂ concentration is higher, possibly because of the excess use of biomass burning in that area.

Figure 4. Seasonal Variation (winter, summer, monsoon, and post monsoon) graphs of SO₂ at all monitoring stations for study period 2016-2020.
3.2.3 NO\textsubscript{2} variation Seasonal variation of NO\textsubscript{2} concentration has been depicted in figure 5 and shown in table 5, where Hazratganj and Talkatora [figure 5(a), (g)] shows a gradual increase in NO\textsubscript{2} concentration for almost all the seasons with a maximum concentration of 37.20 l/g/m\textsuperscript{3} and 38.40 l/g/m\textsuperscript{3} during post-monsoon of 2020. Sarai Mali Khan and Ansal TC [figure 5(b), (c)] shows almost similar variation for the entire study period, with their peak concentration being 35.00 l/g/m\textsuperscript{3} and 34.40 l/g/m\textsuperscript{3} for winter of 2019 and post-monsoon of 2020, respectively. Gomtinagar [figure 5(d)] has its peak concentration of 33.33 l/g/m\textsuperscript{3} during the summer of 2019. Mahanagar and Aliganj [figure 5(e), (f)] show their peak concentration of 34.90 l/g/m\textsuperscript{3} and 35.40 l/g/m\textsuperscript{3} during post-monsoon of 2020 and winter of 2019, respectively. The concentration of NO\textsubscript{2} is higher in the postmonsoon season may be because of the extravehicular activity, which was not in use in the monsoon season. The concentration is significantly less at the Talkatora monitoring station. On this industrial site, the traffic of vehicles may be less as compared to the other monitoring sites in the commercial and residential areas.

3.3 Area-wise variation

Area-wise variation of all monitoring stations for PM\textsubscript{10}, SO\textsubscript{2}, and NO\textsubscript{2} concentration has been plotted in figure 6 and tabulated in table 6(a), (b), (c), respectively. As far as PM\textsubscript{10} concentration at commercial stations [figure 6(a)] is concerned, Hazratganj leads amongst other stations with its peak concentration of 323.05 l/g/m\textsuperscript{3} in 2017, followed by Sarai Mali Khan, Gomtinagar, and Ansal TC, which is for commercial areas. Still, the concentration was more in the industrial areas as compared to the others. Talkatora, an industrial station, has its peak concentration of 229.43 l/g/m\textsuperscript{3} in 2018, whereas Mahanagar and Aliganj showed a minimum concentration of 174.75 l/g/m\textsuperscript{3} and 174.72 l/g/m\textsuperscript{3} in 2019 and 2018, respectively. SO\textsubscript{2} concentration is [figure 6(b)] maximum at Sarai Mali Khan (8.94 l/g/m\textsuperscript{3}), followed by Hazratganj, Gomtinagar, and Ansal TC, which is for commercial areas. Still, the concentration was more in the industrial areas as compared to the others. Talkatora, the industrial area, has its peak concentration of 9.13 l/g/m\textsuperscript{3} in 2017.
m³, followed by Mahanagar and Aliganj for the residential area. For NO₂ concentration [figure 6(c)], Hazratganj and Sarai Mali Khan shows competing for variation as the former has its maximum concentration of 31.51 µg/m³ in 2020, whereas the latter has its maximum concentration of 31.86 µg/m³ in 2019. For industrial and residential areas, Talkatora leads with a maximum NO₂ concentration of 30.32 µg/m³, followed by Mahanagar and Aliganj. So, the comparison of all areas shows that the concentration of the pollutants was higher in the areas where the industries are placed. Hence, the government has to look after to control the pollution in the industrial region.

3.4 Wind rose diagram

Figure 7 shows wind rose diagrams for Lucknow city, plotted using hourly datasets for the study period 2016-2020 to get a clear view of wind speed and direction variation over the city. During the winter season [figure 7(a)], the prominent wind direction is found to be west (nearly 28% of the total study period), with wind speed in the range of 2-2.5 m/s. So, the concentration of pollutants is carried mainly from the west direction in the winter season. Other considerable components include wind from west-north-west and north-west directions, and other smaller components include wind from east, west-south-west, and south-west directions. During summer [figure 7(b)], the predominant wind entering the city is from east, north-west and west (nearly 40%), with wind mainly having a speed of 2-2.5 m/s. As a result, pollutants come into the city from different directions, such as northwest and east. Along with this, more minor components of wind direction include east, south-east, north-east, east-south-east, etc. Monsoon season [figure 7(c)] experiences wind mainly from the east direction for nearly 35% of the total study period (3-3.5 m/s and 1.5-2 m/s) and negligibly from east-south-east, south east, north-east, south-west, etc. As the speed in the monsoon season is less, and the pollutants are washed out due to the rainfall, the concentration in that season is less. Wind directions for post-monsoon [figure 7(d)] mainly comprises north-west followed by west.
and west-north-west respectively, nearly 60% with wind speeds ranging from 2 to 2.5 m/s. From the annual and seasonal variation it has been seen that the concentration of pollutants is more in the post-monsoon season. Most pollutants are carried from the west and north-west direction, i.e., from the Delhi region of the country, which is a highly congested industrial area. It may be the cause of pollution increase in Lucknow city in the post-monsoon season.

### 3.5 Trajectory model

Seasonal back trajectory analysis is carried out for Lucknow to study the aerosol pathways from various sources at the height of 500 meters above ground level, using the HYSPLIT4.0 model and GDAS 1° data [40]. It is estimated that 48-hour air mass isentropic back trajectories at Lucknow for 6-hour intervals (i.e., 00, 06, 12, and 18 UTC each day), emphasizing the movement of aerosols from various places. Plots for 0.5° resolution have been generated from the online version of HYSPLIT4.0 and shown in figures 8(i)a–d, figures 8(ii)a–d, figures 8(iii)a–d, and figures 8(iv)a–d for monsoon, post-monsoon, winter, and summer season, respectively. For the trajectory analysis, the day on which the concentration of pollutants is maximum over the entire study period has been selected for every season. Thus, for monsoon (8 June 2017, 298.24 μg/m³), post-monsoon (8 November 2017, 323.5 μg/m³), winter (8 December 2017, 467.58 μg/m³), and summer (8 May 2017, 429.71 μg/m³) has been selected. Trajectories plot was selected the trajectory frequency analysis. According to this, a trajectory will start from a single position and time steps every 6 hours, sum the frequency with which the trajectory passes over a grid cell, and then normalize the total number of trajectories.

For monsoon season in figures 8(i)a–d, it was analysed by using four frequency analyses, i.e. trajectories passing through (a) grid square/trajectories, (b) endpoints per grid square/trajectories, (c) endpoints per grid square/total, and (d) endpoints per grid square/maximum. For the particle movement [figures 8(i)-(iv)], post-monsoon [figure 8(ii) b], winter [figure 8(iii) b], and summer [figure 8(iv) b] shows potential source regions

| SEASONS     | SEASONAL CONCENTRATION OF NO₂ (in μg/m³) |
|-------------|------------------------------------------|
|             | STATIONS 2016 | 2017 | 2018 | 2019 | 2020 |
| WINTER      | HAZRATGANJ    | 30.41 | 30.78 | 32.27 | 34.50 | 35.71 |
|             | SARAI MALI KHAN | 32.71 | 29.44 | 31.14 | 35.00 | 34.88 |
|             | ANSAL T.C.    | 30.66 | 27.01 | 28.78 | 32.14 | 32.78 |
|             | GOMTI NAGAR   | 31.28 | 28.67 | 30.11 | 32.93 | 32.82 |
|             | MAHANAGAR     | 30.66 | 28.76 | 33.14 | 32.54 | 34.42 |
|             | ALIGANJ       | 33.13 | 27.50 | 27.58 | 35.41 | 33.70 |
|             | TALKATORA     | 31.15 | 30.50 | 33.30 | 34.49 | 35.62 |
| SUMMER      | HAZRATGANJ    | 27.77 | 27.03 | 28.94 | 31.97 | 36.22 |
|             | SARAI MALI KHAN | 27.63 | 27.93 | 27.62 | 29.90 | 29.51 |
|             | ANSAL T.C.    | 27.43 | 25.00 | 26.33 | 29.60 | 31.17 |
|             | GOMTI NAGAR   | 28.80 | 26.57 | 27.29 | 29.43 | 33.30 |
|             | MAHANAGAR     | 28.43 | 26.50 | 27.85 | 28.54 | 33.53 |
|             | ALIGANJ       | 28.23 | 25.37 | 26.33 | 28.43 | 31.62 |
|             | TALKATORA     | 28.27 | 28.10 | 28.84 | 30.42 | 32.43 |
| MONSOON     | HAZRATGANJ    | 23.35 | 22.27 | 26.99 | 27.37 | 29.12 |
|             | SARAI MALI KHAN | 23.63 | 22.50 | 27.65 | 29.73 | 27.35 |
|             | ANSAL T.C.    | 21.73 | 20.23 | 23.69 | 26.37 | 27.13 |
|             | GOMTI NAGAR   | 21.88 | 21.19 | 25.34 | 26.28 | 27.45 |
|             | MAHANAGAR     | 23.28 | 21.42 | 25.22 | 27.00 | 26.90 |
|             | ALIGANJ       | 21.63 | 20.50 | 22.95 | 26.96 | 27.48 |
|             | TALKATORA     | 23.33 | 22.15 | 27.26 | 28.75 | 29.89 |
| POST MONSOON| HAZRATGANJ    | 27.50 | 29.60 | 35.16 | 31.24 | 37.20 |
|             | SARAI MALI KHAN | 27.25 | 26.64 | 32.34 | 34.32 | 34.80 |
|             | ANSAL T.C.    | 25.70 | 22.66 | 29.66 | 28.17 | 34.40 |
|             | GOMTI NAGAR   | 27.05 | 26.10 | 32.84 | 31.47 | 31.30 |
|             | MAHANAGAR     | 26.30 | 25.81 | 31.31 | 32.58 | 34.90 |
|             | ALIGANJ       | 25.75 | 23.23 | 29.58 | 32.25 | 34.25 |
|             | TALKATORA     | 28.50 | 30.03 | 35.82 | 35.73 | 38.40 |
from north-westerly directions and extent is crossing Kanpur city during all three seasons. For the monsoon season, it showed in figures 8(i) a–d that the reversal of wind and movement is from a north-easterly direction over the city. During the monsoon season, marine air from the Arabian Sea and the Bay of Bengal surrounded Lucknow city, and rain washes out pollution in the atmosphere, resulting in lower concentrations. However, during the summer, winter, and post-monsoon seasons the wind from the Thar Desert may deliver the aerosols. As a result, the aerosol concentration is high from November to April. During the post-monsoon season, biomass, coal, and fossil fuel combustion increase aerosol concentration. In the winter season, particulate matter concentration is similar to the monsoon season, except for the pollutants from the Thar desert, which increase in the concentration of aerosol particles in the atmosphere.

The results studied here show that the potential source of pollution for the particulate matter may not only be localized but also be mainly transported from the north-westerly direction. The capital of the country, Delhi, is situated in the west direction (a distance of 550 km from Lucknow) may also contribute to the pollution level over Lucknow city in such a way that air mass particles moving from the west direction contribute more to the pollution for most of the seasons. The high levels of particulate matter in the study area also suggest that all the strategies reduce the locally generated pollution in the area failed to achieve the desired results.

3.6 Dispersion model

The HYSPLIT4.0 dispersion modelling has been applied for pollution dispersion in Lucknow city. HYSPLIT4.0 dispersion modelling uses pollution dispersion during various seasons (Winter, Summer, Monsoon, and Post-Monsoon). The day of maximum concentration over the entire study period in each season was chosen and focused on the release of a unit mass dispersion of aerosols for selected cases of winter (8 December 2017), summer (8 May 2017), monsoon (8 June 2017), and post-monsoon (8 November 2017). It depicts that the maximum value of the pollutant concentration was in the year 2017 over Lucknow city. For the dispersion of pollutants, the online version of HYSPLIT4.0 uses for 24 hours with average periods of 6 hours each for Backward dispersion. All the results are shown in figure 9(i) for winter, figure 9(ii) for summer, figure 9(iii) for monsoon, and figure 9(iv) for post-monsoon. The star symbol indicates the concerned city Lucknow with four concentric circles at 50 Km each.

If analysed in the winter dispersion trend [figures 9(i) a–d], where it can find that, for 6h averaging in figure 9(i)a,
the plume is arriving from the northwest direction. Going back for 12 hours, 18 hours, and 24 hours, figures 9(i) b, c, d respectively, shows that the plume’s direction is from the northwest. After 12 hours averaging in figure 9(i) c, the plume covers the fourth concentric circle, 200 km away from Lucknow, which means the plume’s pollution crosses Kanpur city around 12-18 hours back. Figure 9(i) d shows the plume goes further northwest, but the concentration was less than expected. However, figures 9(iv) a–d show that the plume’s concentration was from north to northwest for the post-monsoon season. Compared to the winter season, for 18 hours averaging

Table 6. Area Wise Categorization of all Monitoring stations for the study period 2016-2020.

(a) Average concentration of PM$_{10}$($\mu$g/m$^3$)

| Type       | Year  | 2016    | 2017    | 2018    | 2019    | 2020    |
|------------|-------|---------|---------|---------|---------|---------|
| Commercial | HAZRATGANJ | 237.68  | 323.05  | 244.95  | 197.76  | 211.21  |
|            | SARAI MALI KHAN | 216.33  | 243.25  | 230.86  | 216.38  | 163.56  |
|            | ANSAL T.C. | 204.13  | 197.09  | 208.84  | 201.09  | 166.61  |
|            | GOMTI NAGAR | 214.50  | 233.55  | 218.26  | 190.02  | 158.96  |
| Residential | MAHANAGAR | 198.13  | 212.06  | 204.50  | 169.28  | 189.26  |
|            | ALIGANJ | 211.87  | 199.28  | 174.73  | 174.75  | 174.68  |
| Industrial | TALKATORA | 216.59  | 214.07  | 229.43  | 224.60  | 195.80  |

(b) Average concentration of SO$_2$(µg/m$^3$)

| Type       | Year  | 2016    | 2017    | 2018    | 2019    | 2020    |
|------------|-------|---------|---------|---------|---------|---------|
| Commercial | HAZRATGANJ | 7.77    | 8.33    | 8.39    | 8.61    | 7.52    |
|            | SARAI MALI KHAN | 7.98    | 8.70    | 8.53    | 8.94    | 7.38    |
|            | ANSAL T.C. | 7.24    | 7.27    | 7.63    | 8.40    | 6.86    |
|            | GOMTI NAGAR | 7.42    | 8.11    | 8.15    | 8.14    | 7.44    |
| Residential | MAHANAGAR | 7.54    | 8.24    | 7.88    | 7.84    | 7.30    |
|            | ALIGANJ | 7.48    | 7.48    | 7.26    | 7.63    | 7.06    |
| Industrial | TALKATORA | 7.92    | 8.24    | 7.96    | 8.62    | 7.73    |

(c) Average concentration of NO$_2$(µg/m$^3$)

| Type       | Year  | 2016    | 2017    | 2018    | 2019    | 2020    |
|------------|-------|---------|---------|---------|---------|---------|
| Commercial | HAZRATGANJ | 26.91   | 26.81   | 30.16   | 30.95   | 31.51   |
|            | SARAI MALI KHAN | 27.50   | 28.28   | 29.30   | 31.86   | 29.11   |
|            | ANSAL T.C. | 26.05   | 23.52   | 26.62   | 28.92   | 29.36   |
|            | GOMTI NAGAR | 26.82   | 25.28   | 28.27   | 29.60   | 30.02   |
| Residential | MAHANAGAR | 26.91   | 25.26   | 28.87   | 29.70   | 30.21   |
|            | ALIGANJ | 26.84   | 23.92   | 26.06   | 30.32   | 29.92   |
| Industrial | TALKATORA | 27.38   | 27.04   | 30.59   | 31.77   | 31.01   |

Figure 7. Wind rose diagram for Lucknow city for various seasons as (a) winter, (b) summer, (c) monsoon, and (d) post-monsoon.
Figure 8. Maps of Trajectory frequencies analysis using HYSPLIT4.0 for air mass particles over (i) Monsoon, (ii) Post-Monsoon, (iii) Winter and (iv) Summer season using 500 m AGL, 48-hour isentropic back trajectories at 6-hour intervals [i.e. (a) 00, (b) 06, (c) 12, and (d) 18 UTC each day] for all four seasons. Star mark shows the location of the city.
concentration, the dispersion is nearest to the city (around 100 km area, i.e., second concentric circle) in the Post-
monsoon season. Figure 9(iv) c shows the cloudy condi-
tion during this season because the mixing height could be
low and the release of smoke in the horizontal direction, as
also seen in the trajectory analysis.

24 h average backward dispersion for summer and
monsoon seasons are shown in figures 9(ii) a–d and
figures 9(iii) a–d, respectively. Figures 9(ii) a–d for summer shows, that the direction of the plume is coming from the east-south direction, which is dispersed in and around of 200 km area around Lucknow after 24 h averaging. More plume concentration is arriving from the east direction for the monsoon season from figures 9(iii) a–d. After an 18-hour average, plume concentration is within a 100 km area around Lucknow, which shows less concentration compared to the summer season in figure 9(ii) d and figure 9(iii) d. It could be because the rain drops wash off the particles in the atmosphere to the ground. The results demonstrate that the plumes are advecting from the north-west in the winter and post-monsoon seasons, and east-south in the summer and monsoon seasons.

3.7 Wavelet analysis

The wavelet transformation is used to crosscheck the spatial variation of periodicity in the concentration of RSPM for the entire study period from 2016 to 2020. All seven monitoring stations are considered for the analysis. The wavelet power spectrum using Morlet wavelet for a Gaussian white noise normalized by standard deviation has been shown in figures 10(a)-(g). The scalograms indicate that the semi-annual periodicity has been observed for RSPM concentration at all the stations. However, the annual periodicity has been observed only for five stations, i.e., Aliganj, Ansal TC, Gomtinagar, Mahanagar, and Talkatora. Hazratganj and Sarai mali khan has not been observed for annual periodicity for the concentration of RSPM based on Wavelet transform. However, these monitoring stations are not far from each other on the city premises, may be concluded that there is semi-annual and annual periodicity in RSPM concentration variations over the entire Lucknow city.

4. Conclusions

The present study reported the analysis of variation in the annual average concentration of RSPM, SO$_2$, and NO$_2$ in Lucknow city from 2016 to 2020. Hazratganj, Aliganj,
Ansal TC, Gomtinagar, Mahanagar, Sarai Mali Khan, and Talkatora were considered for the present study. The variation in annual, seasonal and area-wise concentrations of all three pollutants, viz. RSPM, SO₂, and NO₂ have been studied. The annual average concentration of RSPM varies from 148.74 to 323.05 μg/m³, SO₂ from 7.11 to 8.94 μg/m³, and NO₂ from 23.52 to 31.86 μg/m³ at all the seven monitoring stations. The concentrations of RSPM was observed to be higher than the standard prescribed by CPCB. On the other hand, the concentrations of SO₂ and NO₂ were observed to be below the standards. From seasonal variation comparison, the maximum concentration of RSPM observed in the post-monsoon season ranges from 160.15 to 447.47 μg/m³.

Figure 9. Dispersion maps using HYSPLIT4.0 for Winter (8 December 2017) shown in Figures [i (a) - (d)], and Summer (8 May 2017) shown in Figures [ii (a) - (d)], Monsoon (8 June 2017) shown in Figures [iii (a) - (d)], and Post-Monsoon (8 November 2017) shown in Figures [iv (a) - (d)], starting at 12 UTC of day averaged for 06 h back (a), 12 h back (b), 18 h back (c), and 24 h back (d) in time. Symbol star denotes the Lucknow Monitoring Station Location.
As the monsoon season arrives, the concentration is reduced compared to the other seasons due to the rain falling at all the monitoring stations. The concentrations of SO₂ and NO₂ were observed in the range of 5.55 - 10.94 μg/m³ and 20.23 - 38.40 μg/m³, respectively, for all the seasons. Area-wise concentration concludes that the maximum pollution occurs in the Industrial areas compared to the Commercial and residential. The effect of the lockdown due to the COVID-19 pandemic shows a significant decrease in Lucknow city’s pollution level for 2020 from the collected data. The annual average concentration of RSPM observed to be high at all the stations, and was above the prescribed standard (100 μg/m³) during the study period even in the COVID-19 Lockdown. According to trajectories, winds mainly cause aerosol movement from developed areas and cities, blowing from north-westerly direction throughout the year. The present study clearly indicates that it is not only locally generated pollution but is transported mostly from the nearby industrialised and urbanised areas which are critically affecting the air quality of Lucknow city. This may be the reason for deteriorating the air quality of the city despite implementing the measures by Government of India or local urban body (LUB). This observation has also been confirmed by dispersion analysis by HYSPLIT4.0 for instances selected based on maximum concentration for different seasons in the city over the entire study period. For the study period, the RSPM time-series data shows the existence of annual and semi-annual periodicity. However, further data collection and analysis in the neighbourhood of Lucknow city and theoretical and experimental understandings of pollution discharge and source apportionment studies across the region are required. The findings reveal that the control of particulate matter pollution in the city is a significant

Figure 10. Wavelet power spectrums for RSPM concentration at monitoring stations i.e. (a) Hazratganj, (b) Aliganj, (c) Ansal TC, (d) Gomtinagar, (e) Mahanagar, (f) Sarai Mali Khan, and (g) Talkatora using, Morlet Mother Wavelet.
concern and has an alarming situation compared to SO$_2$ and NO$_2$ pollutants.

**Nomenclature**

- **RSPM**: Respirable Suspended Particulate Matter
- **PM$_{10}$**: Particulate matter particle size less than 10 $\mu$m
- **PM$_{2.5}$**: Particulate matter particle size less than 2.5 $\mu$m
- **SO$_2$**: Sulfur dioxide
- **NO$_2$**: Nitrogen dioxide
- **RDS**: Respirable dust sampler
- **CPCB**: Central Pollution Control Board
- **NAMP**: National Ambient Monitoring Programme
- **SAMP**: State Ambient Monitoring Programme
- **UPPCB**: Uttar Pradesh Pollution Control Board
- **HYPLIT4.0**: Hybrid Single-Particle Lagrangian Integrated Trajectory model version 4
- **NCEP**: National Centers for Environment Prediction
- **NCAR**: National Center for Atmospheric Research
- **GDAS**: Global Data Assimilation System
- **AGL**: Above Ground Level
- **NOAA**: National Oceanic and Atmospheric Administration
- **$\Psi_0(\eta)$**: Wavelet Function
- **$\omega_0$**: Non-dimensional frequency
- **$\eta$**: Non-dimensional time parameter
- **ANN**: Artificial Neural Network
- **MATLAB**: MATrix LABoratory

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