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# Identifying source apportionment of atmospheric particulate matter and gaseous pollutants using receptor models : A case study of Bengaluru, India

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**सार –** **कणीय पदार्थों** PMs ($PM_{2.5}$, $PM_{10}$) **और गैसीय प्रदूषकों जैसे कार्बन मोनोऑक्साइड** (CO), **मीथेन** ($CH_4$), **नाइट्रोजन के ऑक्साइड** (NOx: NO **और** $NO_2$), **गैर-मीथेन हाइड्रोकार्बन** (NMHCs), **सल्फर डाइऑक्साइड** ($SO_2$) **के डेटा अमोनिया** ($NH_3$) **के साथ** 1 **जनवरी** 2017 **से** 20 **मार्च** 2018 **तक बेंगलुरु में पांच अलग-अलग स्थानों पर एकत्र किए गए। इस शोध कार्य का प्राथमिक उद्देश्य भारत के बेंगलुरु में रिसेप्टर मॉडल का उपयोग करके वायुमंडलीय कण पदार्थ और गैसीय प्रदूषकों के स्रोतों की पहचान करना है। इसे निष्पादित करने के लिए, रिसेप्टर मॉडल, अर्थात् सशर्त द्विचर संभाव्यता फ़ंक्शन (सीबीपीएफ) और केंद्रित भारित प्रक्षेपवक्र (सीडब्ल्यूटी) का प्रयोग किया गया है। कंडीशनल बाइवेरिएट प्रोबेबिलिटी फंक्शन (सीबीपीएफ) से पता चलता है कि, सालाना, उत्तर-पूर्व दिशा में कम हवा की गति** (<2 **समुद्री मील**) **के दौरान रिसेप्टर साइटों पर कणीय पदार्थों की अधिकतम सांद्रता का पता लगाया गया था, इससे यह स्पष्ट होता है कि लंबी दूरी तक का परिवहन एक आवश्यक भूमिका नहीं निभाता है। कणीय पदार्थों की उच्च सांद्रता के परिवहन में और उनके प्राथमिक स्रोत क्षेत्र को स्थानीयकृत किया जा सकता है। संकेंद्रित भारित प्रक्षेपवक्र (सीडब्ल्यूटी) विश्लेषण से पता चलता है कि, ऋतुनिष्ठ रूप से, गर्मियों में लगभग** 37% **का उच्चतम वायु द्रव्यमान देखा गया था, जबकि सबसे कम मॉनसूनोत्तर ऋतु में** (13%) **था। लंबी दूरी से परिवहन किए गए** $PM_{2.5}$ **का महत्वपूर्ण योगदान मॉनसून के दौरान था, और** $PM_{10}$ **के मामले में, यह गर्मियों में था। अध्ययन से पता चलता है कि कणीय पदार्थों और गैसीय प्रदूषकों का लंबी दूरी तक का परिवहन महत्वपूर्ण नहीं था और इसे स्थानीयकृत प्रेक्षित किया गया था।**

**ABSTRACT.** The data of Particulate matter PMs ($PM_{2.5}$, $PM_{10}$) and Gaseous Pollutants such as carbon monoxide (CO), methane ($CH_4$), oxides of nitrogen (NOx: NO and $NO_2$), non-methane hydrocarbons (NMHCs), sulfur dioxide ($SO_2$), along with ammonia ($NH_3$) at five different locations across Bengaluru from 1st January, 2017 to 20th March, 2018 were collected. The primary objective of this research work is to identify the sources of atmospheric particulate matter and gaseous pollutants using receptor models in Bengaluru, India. To execute this, receptor models, namely Conditional Bivariate Probability Function (CBPF) and Concentrated Weighted Trajectory (CWT) Analysis, are applied. Conditional Bivariate Probability Function (CBPF) shows that, annually, the maximum concentrations of PMs over receptor sites were detected during low wind speed (< 2 knots) along the north-east direction specifying that the long-range transport does not play an essential role in the transportation of higher concentrations of PM and their primary source region may be localized. Concentrated Weighted Trajectory (CWT) analysis shows that, seasonally, the highest air mass contribution of about 37% was noticed in summer, whereas the lowest was in the post-monsoon season (13%). The significant contribution of $PM_{2.5}$ transported from long distances was during monsoon, and in the case of $PM_{10}$, it was in summer. The study suggests that the long-range transport of PMs and gaseous Pollutants was not vital and was observed to be localized.

**Key words** – Particulate matter, Gaseous pollutants, Long-range transport, Concentrated weighted trajectory analysis.

## 1. Introduction

Due to the tremendous increase in population density along with rapid industries and urbanisation growth, considerable atmospheric pollution has led worldwide. It is an alarming stage in developing countries, especially India and China (in Asia). In India, the air quality is worsening in most megacities compared to

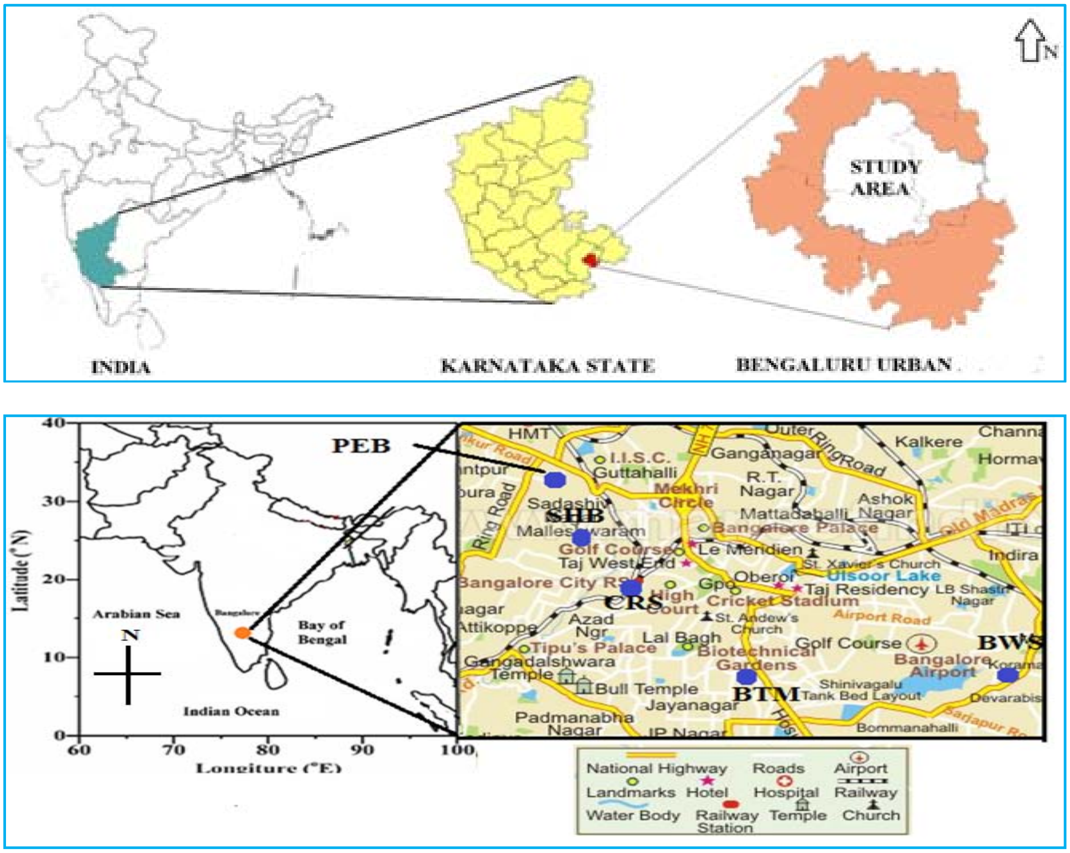


**Fig. 1.** Sampling Location in Bengaluru urban area

Chinese cities. As per the World Health Organization (WHO), around eighteen Indian cities in 2016 were in the top fifty contaminated cities worldwide concerning $PM_{10}$. These high concentrations of particulate matter in ambient air raises mortality and morbidity rate in India (Dholakia *et al*., 2014; Maji *et al*., 2017).

The majority of the Indian Urban and suburban areas face a huge air pollution problem as a result of Urbanization and industrialisation. In this regard, it is essential to figure out the local and regional air quality to examine the possible risks to the environment and health of people. The capital of Karnataka, "Bengaluru", is located in the Southern part of India and is still facing challenges due to atmospheric pollution. Due to vehicular emissions, the city's levels are still very high compared to national and international standards (Thakur, 2017). Vreeland *et al*., 2016, has reported that substantial roadside trash burning in Bengaluru city is a significant source of atmospheric pollution. Besides this, some pollutants could also be carried from long distances. The primary objective of this research work is to identify the sources of atmospheric particulate matter and gaseous pollutants using receptor models in Bengaluru, India. This study is essential to assess the changes in the air quality in Bengaluru city and to develop preventative and mitigation measures.

In this research work, the data on particulate matter, gaseous pollutants and meteorological parameters were collected at five locations (Fig. 1). These locations were operated by Government agencies called Central and State pollution control boards that represents different environments (Table 1).

2.1 *Statistical analysis for source and sink identification by different receptor models*

Back-Trajectory Analysis (BTA) has been used extensively to evaluate the potential effect of long-distance transport of pollutants. This study calculated 5-day back trajectories arriving at 1 kilometre above the ground level every hour from January 2017 to March 2018 using the HYSPLIT-4 model and ARL meteorological datasets (Draxler and Hess, 1998; Stein *et al*. 2015). Further, the cluster analysis, a multidimensional statistical analysis technique, was applied to classify the trajectory data into different transport groups called clusters of a

**TABLE 1**

**Detail report of the sampling stations in Bengaluru urban area**

| Monitoring Station | Short Name | Latitude values | Longitude values | Sampler | Land use pattern |
|---|---|---|---|---|---|
| Byrasandra, Thavarekere Madiwala | BTM | 12.97° N | 77.59° E | $PM_{2.5}$, GPs, MPs | Residential, Commercial |
| Peenya | PEB | 13.03° N | 77.51° E | $PM_{2.5}$, GPs, MPs | Industrial, Residential |
| Kadabesana halli | BWS | 12.93° N | 77.69° E | $PM_{2.5}$, GPs, MPs | Industrial, Residential |
| Sanegurava Halli | SHB | 12.99° N | 77.54° E | $PM_{10}$,GPs, MPs | Residential, Commercial |
| City Railway Station | CRS | 12.97° N | 77.57° E | $PM_{10}$, GPs, MPs | Commercial, Residential, high vehicular density |

similar history. Four clusters for all data during the study period were calculated, providing the best representation of air mass classifications. The Euclidean distance between two paths is calculated as follows.

$$d_{1,2} = \left( \sum_{i=1}^{n} \left[ \left( X_{1i} - X_{2i} \right)^2 + \left( Y_{1i} - Y_{2i} \right)^2 \right] \right)^{1/2} \qquad (1)$$

where 1 and 2 represent trajectories of 1 and 2, with a duration of the corresponding trajectory, ($X_1$, $Y_1$) and ($X_2$, $Y_2$) are coordinates of two locations, and $n$ is the numerous trajectory points. The two trajectories are merged if the distance between them is small. There will be $n$-1 trajectories left after the first round of clustering. The process is repeated until all n trajectories are assigned to one cluster.

2.2. *Concentrated weighted trajectory (CWT) analysis*

The CWT analysis was performed due to the drawback of the PSCF (Potential Source Contribution Function) technique wherein the grid cells could have the same PSCF value when aerosol concentration at the receptor site is slight or exceedingly above the average value. Consequently, efforts are required to differentiate between moderate and vigorous sources. Further, the PSCF value gives the geographical distribution of potential source areas contributing to the receptor site but cannot give information on the contribution of various potential source areas. This limitation is overcome in CWT analysis, which is a method to distinguish source and strength by assigning the values at the receptor site to their appropriate trajectories (Ashbaugh *et al*., 1985; Hsu *et al*., 2003). In the CWT method, the logarithmic mean value is assigned as a weight for the residence time of the trajectory in each grid square as follows:

$$\ln\left(C_{ij}\right) = \frac{1}{\sum_{k=1}^{N} \tau_{ijk}} \sum_{k=1}^{N} \ln\left(c_k\right) \tau_{ijk} \qquad (2)$$

where "$i$" and "$j$" indicate the grid location; "$k$" is the index of trajectory, "$N$" is the number of trajectories; "CK" is a concentration of pollutant arrived in trajectory "$k$"; τ is the residence time of trajectory "$k$" in "$ij^{th}$ grid square"; "$C_{ij}$" is the mean of the concentration of $ij^{th}$ grid square.

2.3. *Conditional bivariate probability function (CBPF)*

Variation of aerosol concentrations with wind speed and wind direction gives a better idea of the source regions (Ropkins and Carslaw, 2012). CPF technique is helpful in finding the directional information of source regions (Ashbaugh *et al*., 1985), (Kim *et al*., 2003; Malby *et al*., 2013; Uria-Tellaetxe and Carslaw , 2014) and it estimates the probability of the measured concentrations surpassing a threshold condition for a given wind sector. CBPF is the continuation of the CPF (Conditional Probability Function) method. The coupling of wind speed to the CPF as the third variable provides additional information on directional source regions. The technique behind CBPF is the ratio of the number of times the bin of the particular wind speed and wind directions when crosses a threshold concentration ($75^{th}$ percentile of the annual mean concentrations are taken as a threshold

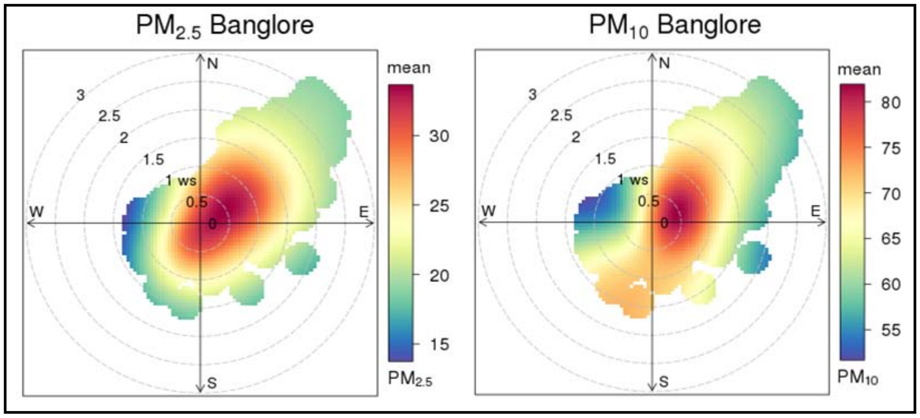


**Fig. 2.** Annual Mean Bivariate Diagram of PMs ($PM_{2.5}$, $PM_{10}$) concerning Wind Speed and Wind Direction in the Bengaluru Urban area

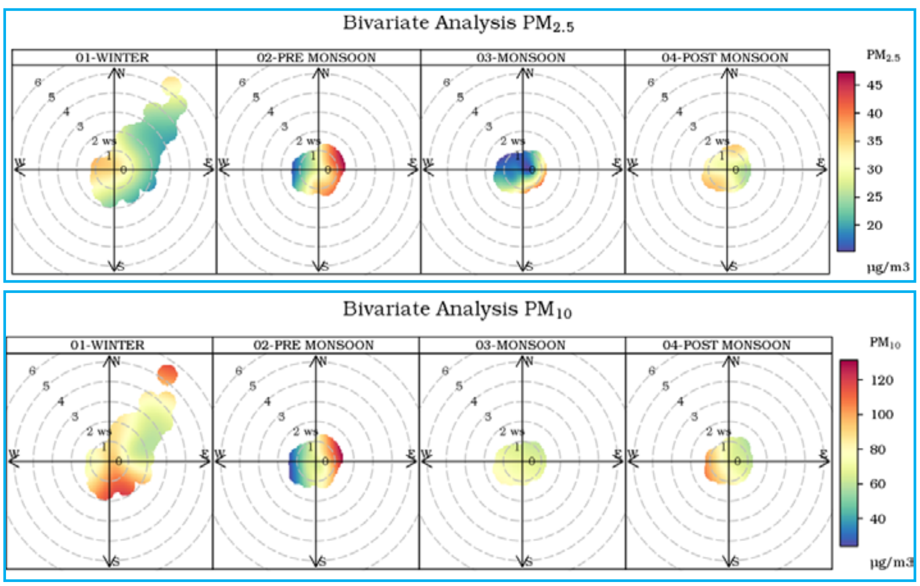


**Fig. 3.** Seasonal-mean Bivariate Diagram of PMs ($PM_{2.5}$, $PM_{10}$) concerning Wind Speed and Wind Direction in the Bengaluru Urban area

value for the estimation of CBPF) of the pollutant to the number of times. It can be represented as :

$$CBPF_{\Delta\theta,\Delta u} = \frac{m_{\Delta\theta,\Delta u}}{n_{\Delta\theta,\Delta u}} \quad (3)$$

Where $m_{\Delta\theta,\ \Delta u}$ indicates the data points in a wind direction $\Delta\theta$ with wind speed interval $\Delta u$ representing concentrations higher than a threshold value. $n_{\Delta\theta,\ \Delta u}$ indicates the data points in that wind direction and wind speed interval. The equation (3) is utilized to identify the local sources and long-range transportation of $PM_{2.5}$ and $PM_{10}$. The selection of threshold concentration C varies based on wind speed, wind direction, emission sources and type of measured pollutant. The ways to select the threshold concentrations are described (Malby *et al.*, 2013; Carslaw, 2015).

## 3. Results and discussion

### 3.1. *Conditional bivariate probability function for source region identification*

In the present study, the Bivariate plots were plotted to show the conditional probabilities for $PM_{2.5}$ and $PM_{10}$ concentration annually and seasonally over Bengaluru and were depicted in Figs. 2&3. Annually, the highest concentrations of $PM_{2.5}$ (>30µg/ m$^3$) and $PM_{10}$ (> 75µg/ m$^3$) in the receptor site were noticed during low wind speed (< 2 knots) along with north-east direction which indicated that the significant PM concentration is

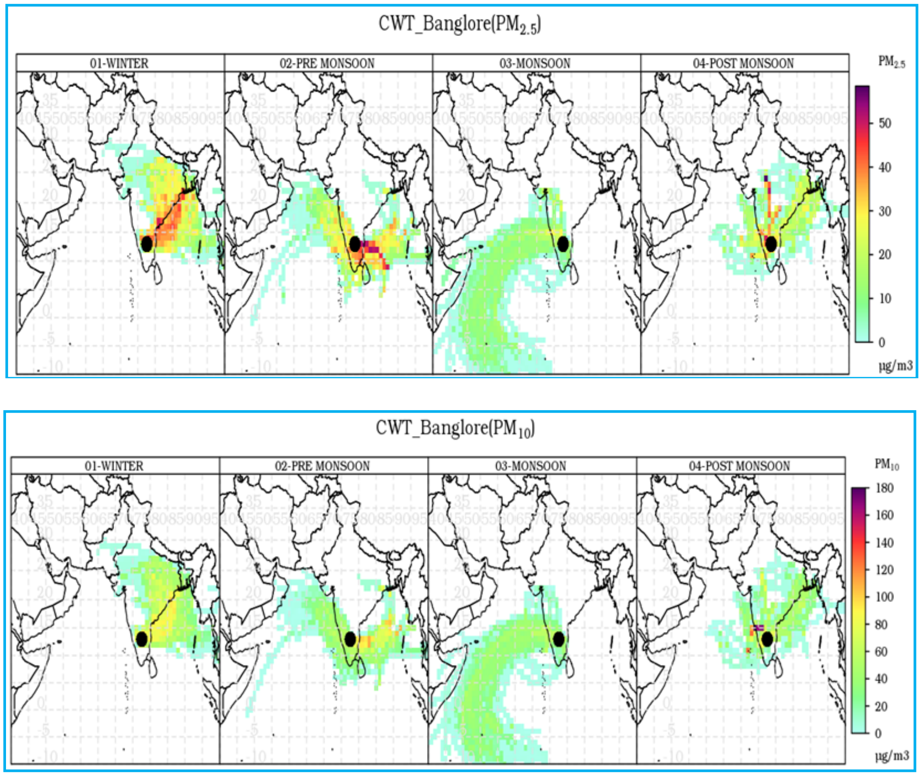


**Fig. 4.** Seasonal Concentrated Weighted Trajectory Analysis of PMs ($PM_{2.5}$, $PM_{10}$) arriving at 1000m Altitude over Bengaluru Urban area

from local sources and rarely experienced long-range transportation. However, the seasonal analysis was observed to differ from the annual study. During low wind speed (< 1 m/s), the $PM_{2.5}$ in winter, as well as post-monsoon period, showed the highest values (> 35 µg/ $m^3$), specifying that the significant source region may be localised. It may be due to the burning of biomass (extreme crop residue burning in October and November months and are responsible for these higher concentrations), whereas, during monsoon, it was much lower due to the washout of particulates. During pre-monsoon, the $PM_{2.5}$ was transported from the northeast-southwest direction when the wind speed was more significant than 3 knots (Wen *et al*., 2018). In the case of $PM_{10,}$ the concentrations were highest (> 120 µg/ $m^3$) in winter, and post-monsoon periods when the wind arrives from a south-east and west direction with wind velocity greater than 4 knots, indicating that some particles are transported from long-distance, however, in the monsoon period, it was localised. In the case of pre-monsoon season, the highest concentrations (> 120 µg/ $m^3$) were observed when the wind arrived from the east direction over the receptor side, which indicates the windblown dust to $PM_{10}$ is a foremost contributor, However, during the post-monsoon, It was from the western part of the city. A study by Charron and Harrison (Charron and Harrison, 2003) has found that a strong WS significantly affects bigger particles compared to minor particles. Another study showed that if the temperature increases, the concentrations of PM increase significantly (Barmpadimos, *et al*., 2012). Charron and Harrison, 2003, reported that the mass concentrations of atmospheric particles reduced drastically due to the washout effect of rain. They also found that the ultrafine particles were significantly higher during the rainy months.

### 3.2. *Concentrated weighted trajectory analysis*

Apart from the significant contribution of PMs ($PM_{2.5,}$ $PM_{10}$) from the local sources and local meteorological conditions, Bengaluru Urban may also experience long-range transportation of particulate matter. The concentrated weighted trajectory (CWT) analysis is the best approach to quantify the contribution of local emissions and transported source of emissions of any pollutants. In the present study, five days back, trajectory data was taken to investigate the role of long-range transport of atmospheric pollutants (as PM) measured over Bengaluru city during different climatic (seasonal) conditions. The back trajectory diagram at all seasons is plotted from 1st Jan, 2017 to Mar, 2018 and depicted in Fig. 4. The contribution of transported and localised

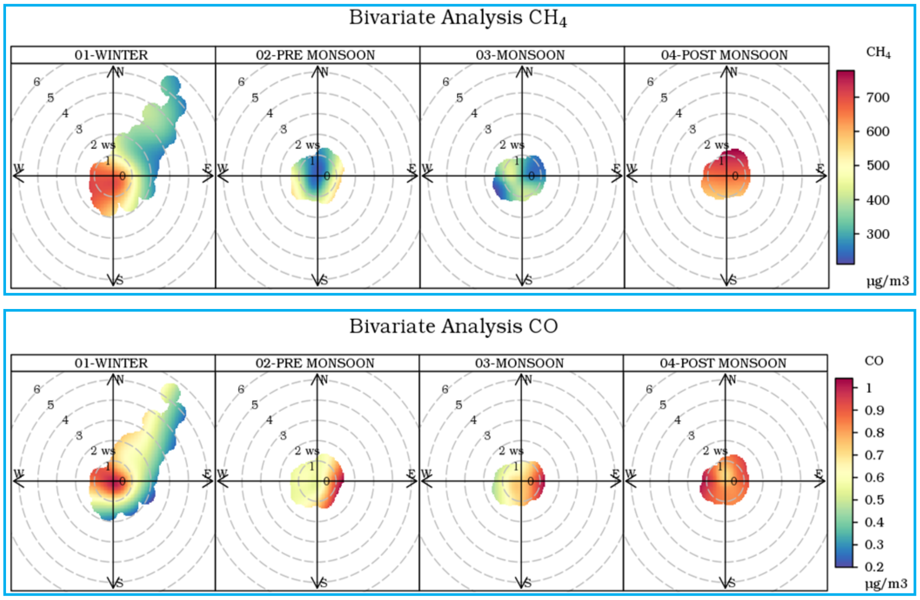


**Fig. 5.** Seasonal Bivariate Plots of CO and $CH_4$ over Bengaluru Urban area

**TABLE 2**

**Season wise transported contributions of PMs ($PM_{2.5}$, $PM_{10}$) over Bengaluru urban**

| Season | $PM_{2.5}$ (observed) | $PM_{10}$ (observed) | Cluster in % Air masses | $PM_{2.5}$ (transported) | $PM_{10}$ (transported) | Transported Contribution (%) $PM_{2.5}$ | Transported Contribution (%) $PM_{10}$ |
|---|---|---|---|---|---|---|---|
| Winter | 38.5 | 85.1 | 27 | 16.9 | 35.6 | 44 | 42 |
| Summer | 31.0 | 72.1 | 37 | 18.2 | 37.7 | 59 | 52 |
| Monsoon | 19.2 | 66.6 | 24 | 12.6 | 23.6 | 66 | 35 |
| Post-monsoon | 32.3 | 76.1 | 13 | 6.6 | 19.3 | 20 | 25 |

sources was estimated from CWT data and depicted in Table. 2. During winter, most of the air masses arrive from the North and Eastern parts of India up to the Bay of Bengal, that side several commercial and industrial cities (such as Chennai, Tirupati, Hyderabad, Vijayawada, Vishakhapatnam, and Guntur) are located, and consequences of this city were higher values of PMs ($PM_{2.5,}$ $PM_{10}$). However, in the summer, air masses pass from Northwest Direction and Easterly, which are also affected by major cities like Mumbai, Pune and Chennai. During the monsoon season, the air masses were entirely from the Southwest, covering the Arabian Sea and significant sources from the sea and two major cities, Kannur and Mysuru. However, in post-monsoon season, the airflow arrived from the continental side, Northwest and northeast (up to Kolkata) direction.

Season-wise transported contributions of $PM_{2.5}$ and $PM_{10}$ over Bengaluru were estimated and depicted in Table 2. The maximum air mass contribution was 37% during pre-monsoon, and the minimum was during post-monsoon (13%). The contribution of transport from a long distance of $PM_{2.5}$ was during monsoon season; however, in the case of $PM_{10}$, pre-monsoon season. The meagre transportation contribution of PMs ($PM_{2.5,}$ $PM_{10}$) was in the post-monsoon season (20 and 25%), respectively. Significant variability in the transported contribution of PMs is due to its topography, climatic conditions and emission sources. The study conducted by Awasthi *et al.*, 2011, reported very high $PM_{2.5}$ (~ 69µg $m^{-3}$) values over Patiala in Punjab, India. They observed that the concentration of $PM_{2.5}$ was high (~78%) due to the burning of rice residues in October and November (post-monsoon period), with maximum values (of 100 and 147 µg/$m^3$). In another study, Badarinath *et al.*, 2006, also reported higher particulate matter due to farmers' setting fire to rice crop residue over the Indo-Gangetic Plains during October and November.

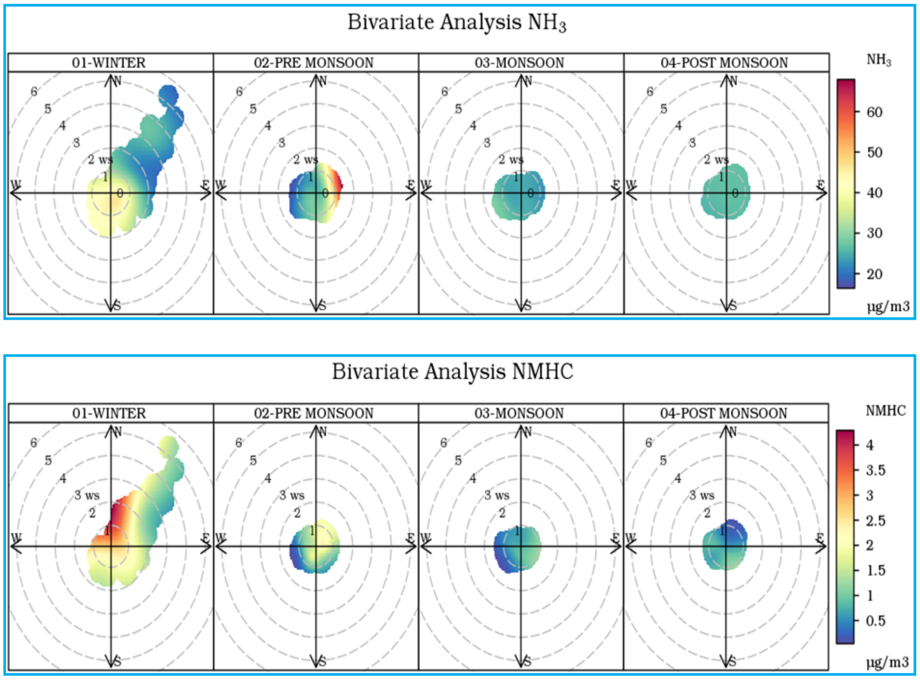


**Fig. 6.** Seasonal Bivariate plots of NMHC and $NH_3$ over Bengaluru Urban area

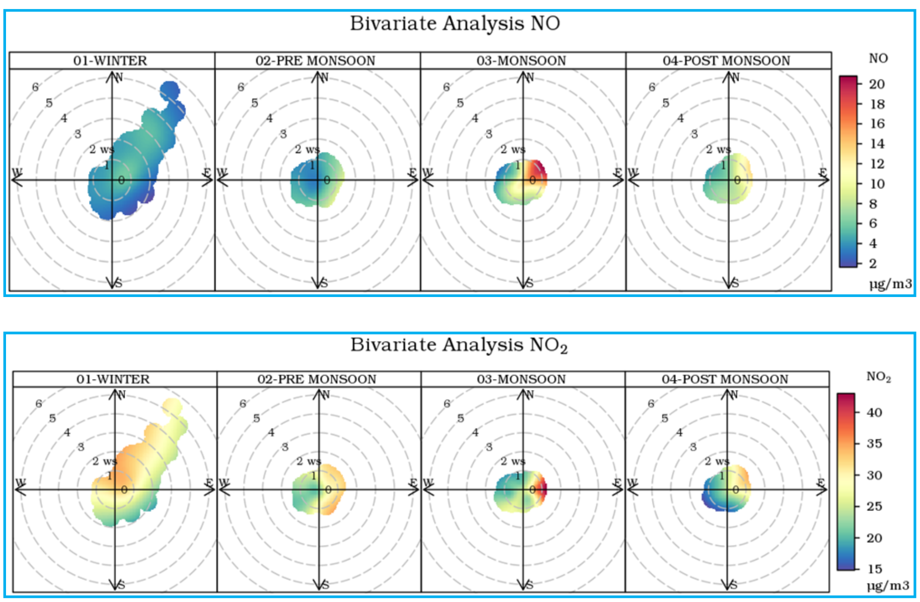


**Fig. 7.** Seasonal Bivariate plots of NO and $NO_2$ over Bengaluru Urban area

3.3. *Bivariate analysis*

The Bivariate descriptive plots are developed to spell out the relationship (the form of the relationship, the dependence of the relationship and the strength of the relationship) between two known variables for their possible source region. The Bivariate seasonal plots were plotted to show the conditional probabilities for the gaseous pollutants ($O_3$, $CH_4$, NMHC, $NH_3$, $SO_2$, CO, NO and $NO_2$) concentration in Bengaluru (Figs. 5-8). In the present study, the highest value of CO and $CH_4$ over the receptor side was during post-monsoon at the lesser wind speed (> 1 knot), which indicates that the significant source of CO and $CH_4$ is from the local source region,

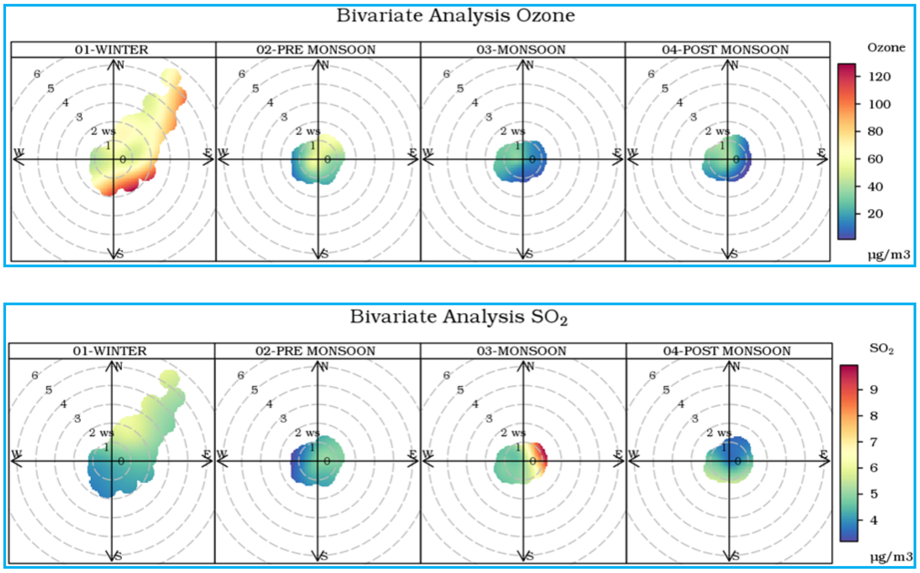


**Fig. 8.** Seasonal Bivariate plots of $SO_2$ and $O_3$ over Bengaluru Urban area

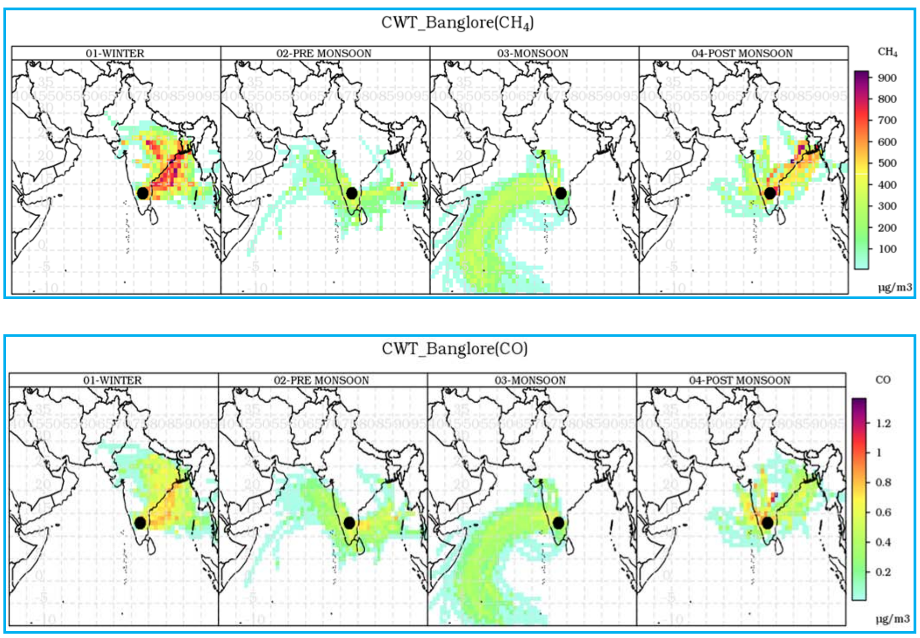


**Fig. 9.** Seasonal Concentrated Weighted Trajectory Analysis for CO and $CH_4$ arriving at 1000 m Altitude over Bengaluru Urban area

However, the concentration of CO and $CH_4$ was lower in the monsoon period by the washing out the effect of rain. During the winter period, when the WS is more significant than 5 m/s along the northeast direction, that indicates that long-range transport plays a crucial role in the transportation of higher concentrations of CO and $CH_4$. The NMHC was lowest in the monsoon and post-monsoon seasons. However, it was highest in the winter when the wind speed was more than 2 m/s in the north direction, indicating the transportation of NMHC. The ammonia concentrations were much higher during winter during calm wind conditions. However, during summer, it was partially transported from the northeast region when the WS was around 1 m/s. In the case of NO, it was observed that it is locally produced instead of transported except in the winter season. The NO concentrations were much higher during the monsoon season when compared to other seasons when the WS was around 1.5 m/s, indicating

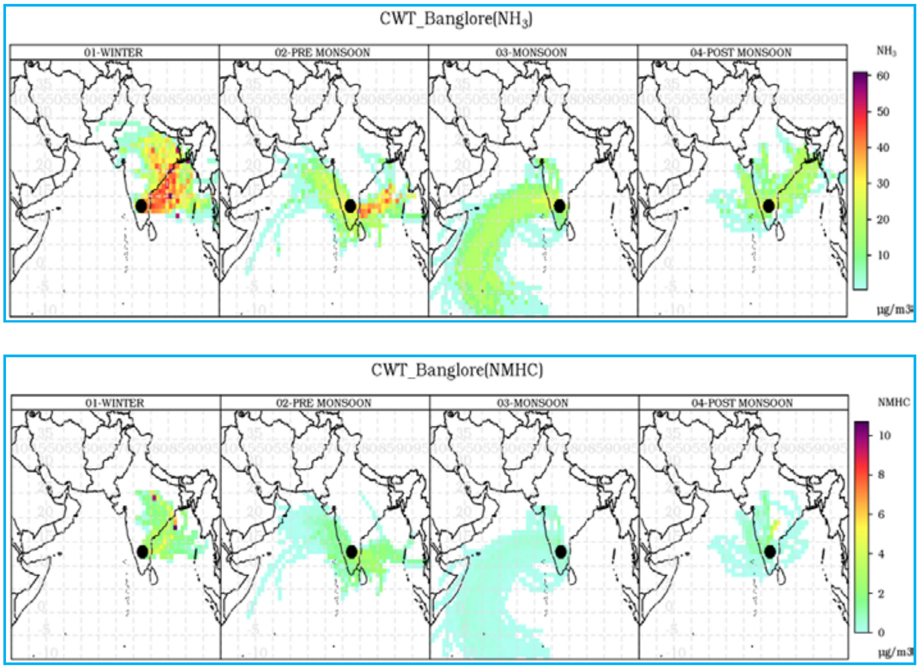


**Fig. 10.** Seasonal Concentrated Weighted Trajectory analysis for NMHC and $NH_3$ arriving at 1000m Altitude over Bengaluru Urban area

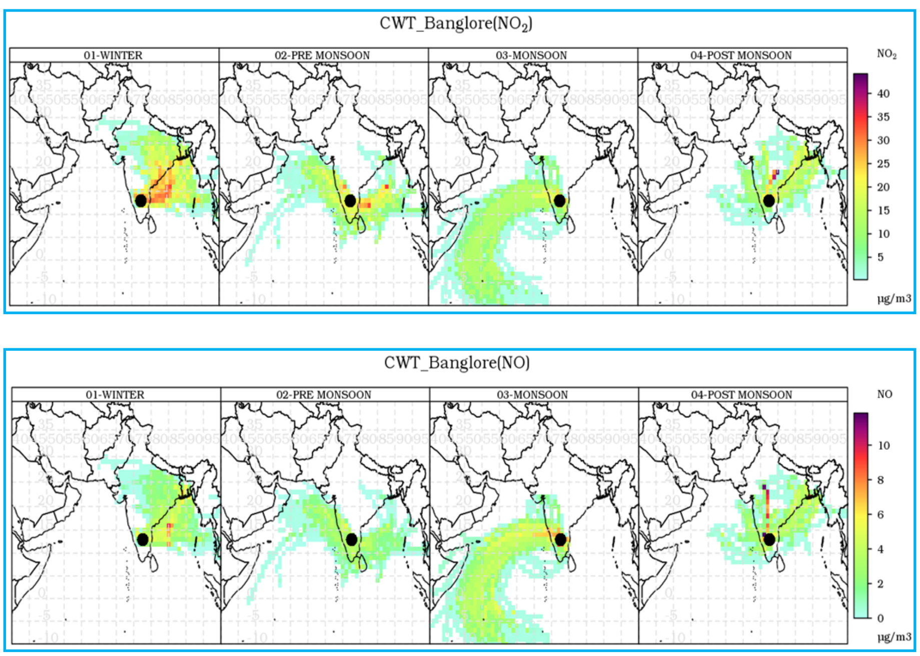


**Fig. 11.** Seasonal Concentrated Weighted Trajectory analysis for NO and $NO_2$ are arriving at a 1000m Altitude over Bengaluru Urban area

that some portion was transported. In the case of $NO_2$, it was highest during winter (more than 40 micrograms per cubic meter) and was transported from the northeastern region. However, it was the second-highest during summer and the wind was from the eastern side when a higher concentration (greater than 35µg/m$^3$) was observed. In monsoon and post-monsoon season, it was localised. In the case of $SO_2$, in the monsoon season, the concentrations were more than 9 µg/m$^3$ when the WS was more than 1m/s from an east direction which indicates the long-range

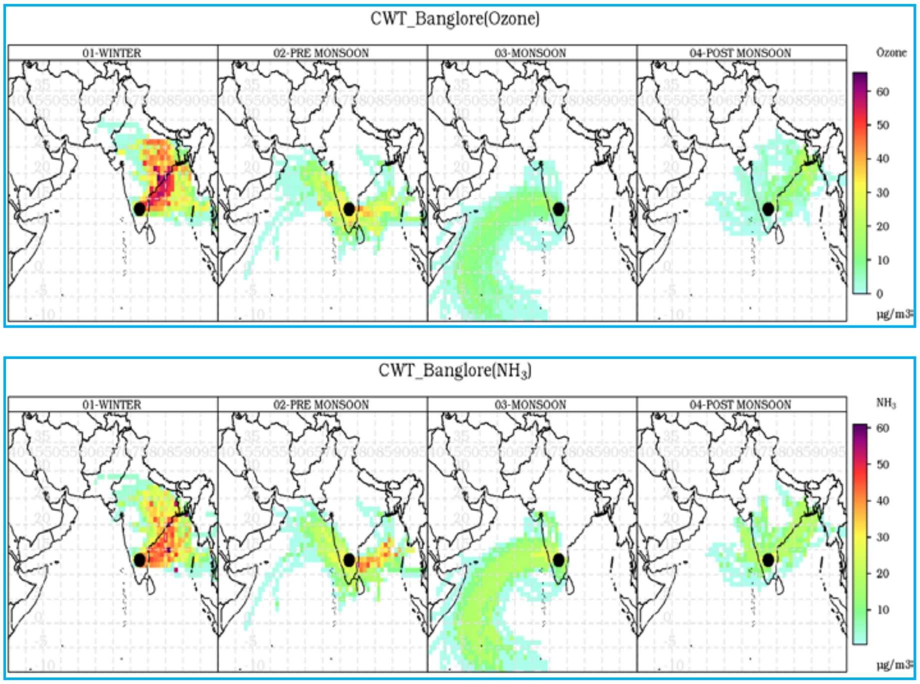


**Fig. 12.** Seasonal Concentrated Weighted Trajectory analysis for $NH_3$ and $O_3$ arriving at 1000 m Altitude over Bengaluru Urban area

**TABLE 3**

**Cluster-wise concentrations of trace gases over Bengaluru urban area**

| Cluster | Cluster (%) | Ozone | NMHC | $NH_3$ | $CH_4$ | CO | NO | $NO_2$ | $SO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| C1 | 27 | 16.55 | 1.49 | 21.16 | 248.07 | 0.33 | 1.94 | 11.39 | 2.18 |
| C2 | 37 | 20.67 | 2.47 | 19.53 | 362.87 | 0.37 | 2.14 | 12.21 | 2.16 |
| C3 | 24 | 7.52 | 0.53 | 9.93 | 164.14 | 0.24 | 1.97 | 7.49 | 1.91 |
| C4 | 13 | 5.64 | 0.14 | 9.20 | 152.97 | 0.19 | 1.98 | 6.50 | 2.19 |
| Average | 100 | 12.60 | 1.16 | 14.95 | 232.01 | 0.28 | 2.01 | 9.40 | 2.11 |

**TABLE 4**

**Annual mean mass concentrations of $PM_{2.5}$ and $PM_{10}$ at different sites over Bengaluru during 2017 and 2018**

| Measured PM | | 2017 | | 2018 | | %* |
|---|---|---|---|---|---|---|
| | | Conc. | SD | Conc. | SD | |
| $PM_{2.5}$ | BTM | 19.95 | 12.03 | 33.99 | 30.50 | 41 |
| | BWS | 16.76 | 10.29 | 26.34 | 16.96 | 36 |
| | PEB | 38.15 | 19.33 | 28.50 | 36.09 | -34 |
| | Mean | 26.73 | 15.59 | 31.13 | 18.87 | 14 |
| $PM_{10}$ | SHB | 36.10 | 15.36 | 58.16 | 35.62 | 38 |
| | CRS | 77.87 | 25.80 | 79.89 | 70.72 | 3 |
| | Mean | 58.05 | 18.92 | 95.61 | 42.55 | 39 |

***** Differences in between 2017 to 2018 transportation of sulfur dioxide, However, during winter, it was transported. In the case of summer and post-monsoon, it was from local sources. In the case of ozone, during winter, it was transported and localised sources; however, in the pre-monsoon season, it was partially transported. Its sources were localised for the rest of the two seasons, monsoon and post-monsoon.

### 3.4. *Concentrated weighted trajectory analysis*

Concentrated Weighted Trajectory (CWT) is a statistical model that combines measured atmospheric pollutant concentrations and back trajectories data to find the possible source region of atmospheric pollutants. Based on earlier research, it was observed that some of the source areas were associated with known industrial sectors, crop residue burning, fossil fuel power plants and the coastal area that was located surrounding the sampling location (Sreekanth, 2007). The present study applied CWT analysis to gaseous pollutants ($O_3$, $CH_4$, NMHC, $NH_3$, $SO_2$, CO, NO, and $NO_2$) over Bengaluru from 1$^{st}$ Jan, 2017 to 31$^{st}$ March, 2018 was depicted in Figs. 9-12. The cluster analysis of the significant air masses passing over the receptor site is given in Table 3. The annual mean mass concentrations of $PM_{2.5}$ and $PM_{10}$ at different sites over Bengaluru during 2017 and 2018 is depicted in Table 4. The annual average values of the surface $PM_{2.5}$ and $PM_{10}$ concentration found increasing (14% and 39% increased in 2018 as compared to 2017 respectively) year-by-year over Bengaluru. For instance, the increasing trends of $PM_{2.5}$ (fine) concentration over BTM and BWS areas are likely related to the production of anthropogenic fine mode particle emissions along with meteorological influence, however, the lower concentrations of $PM_{2.5}$ were observed during 2018 as compared to 2017 at an industrial site (PEB) it is due to impact of meteorological conditions being similar sources of fine particles pollutants over this site mostly from man-made activities.

During winter, most air masses arrive from the north and eastern part of India up to the Bay of Bengal, associated with several commercial and industrial sites such as Chennai, Tirupati, Hyderabad, Vijayawada, Vishakhapatnam and Guntur. These cities have higher concentrations of CO and NOx and $SO_2$. However, during summer, the air masses were from the Northwest and easterly and it is also affected by major cities like Mumbai, Pune, and Chennai. During monsoon, the air masses were utterly from the southwest direction covering the Arabian Sea, the two major cities of Kannur and Mysuru. However, in post-monsoon season, the airflow was from the continental side, *i.e.*, from the northwest and northeast (up to Kolkata) direction. The contribution of gaseous pollutants ($O_3$, $CH_4$, NMHC, $NH_3$, $SO_2$, CO, NO,

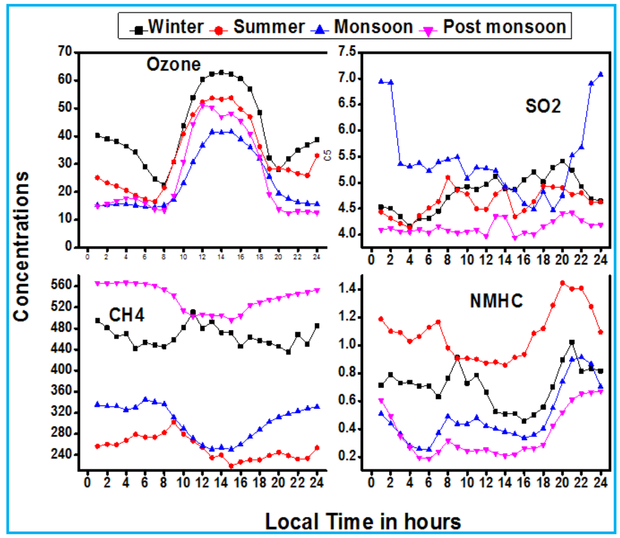


**Fig. 13.** Seasonal diurnal variation of the surface measured $O_3$, $SO_2$, $CH_4$ and NMHC over Bengaluru during the study period

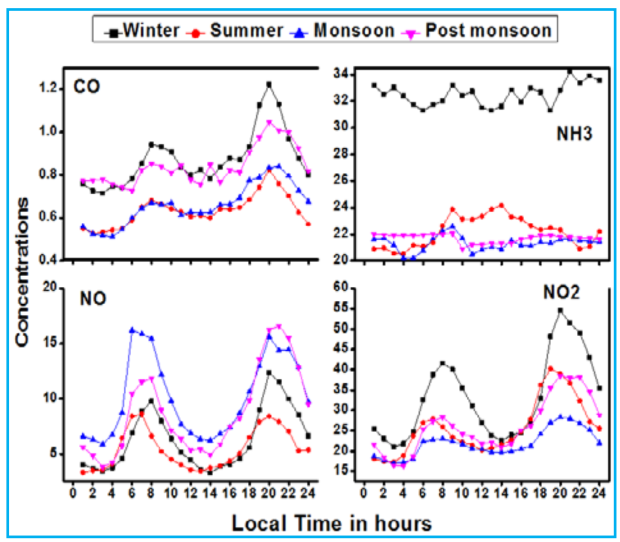


**Fig. 14.** Seasonal diurnal variation of the surface measured CO, $NH_3$, NO and $NO_2$ over Bengaluru during the study period

and $NO_2$) were separated from localised sources and were 38, 54, 100, 46, 56, 62, 56 and 65%, respectively and rest of the contribution was transported (Sutton *et al.*, 1998).

### 3.5. *Ambient concentrations of gaseous pollutants ($O_3$, $CH_4$, NMHC, CO, $NH_3$, NO, $NO_2$ and $SO_2$)*

The ambient concentrations of $O_3$, $CH_4$, NMHC, CO, $NH_3$, NO, $NO_2$ and $SO_2$ were measured over Bengaluru from 1$^{st}$ January 2017 to 20$^{th}$ March 2018 (Figs. 13&14). The daily mean concentrations of $O_3$, $CH_4$, NMHC, CO, $NH_3$, NO, $NO_2$ and $SO_2$ were 35.0 ± 17.50 ppb, 412.8 ± 259 ppm, 1.1 ± 1.1 ppb, 0.7 ± 3.1 ppm, 28.8 ± 15.7 ppb,

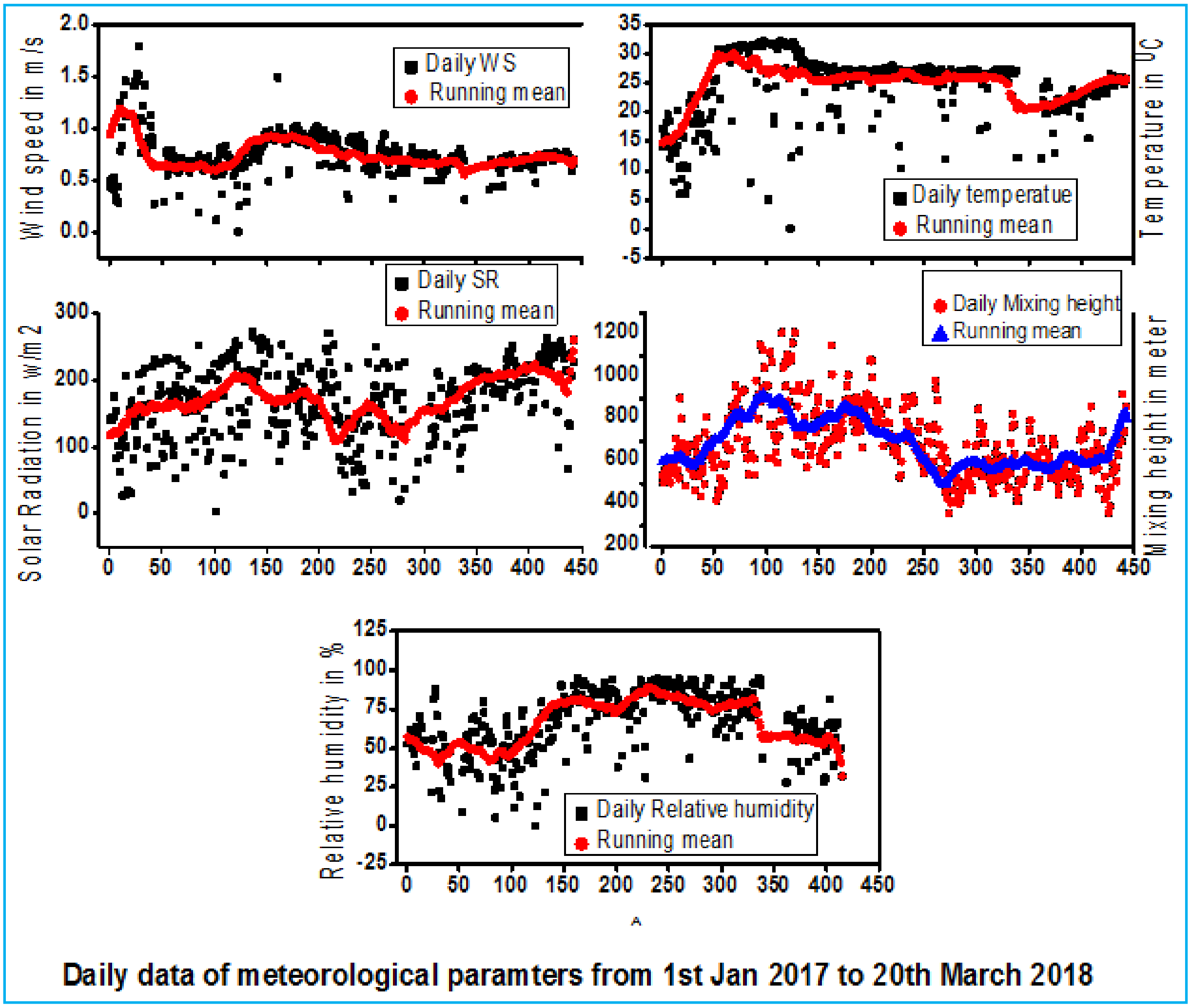


**Fig. 15.** Daily values of met parameters over Bengaluru during the study period

7.2 ± 3.1 ppb, 27.5 ± 8.4 ppb and 4.8 ± 1.6 ppb, respectively. The ozone concentrations over Bengaluru are lower than the World Health Organization (WHO) 8-hour maximum standard (100μg/m$^3$ or 50 ppb) that was established to adequately protect public health (WHO, 2006) and national standard stipulated by Central Pollution Control Board (100 μg/m$^3$: http://cpcb.nic.in/air-quality-standard/). These lower values of surface ozone reflect that there is substantial titration of the ozone by freshly emitted NO from vehicular emission. Significant variability in the annual mean concentrations of $O_3$ was observed in between two monitoring locations over the city side with the highest (43.1 ppb) at BTM and BWS (30.7 ppb). Seasonally, during the winter period, the mean $O_3$ concentration was highest (mean = 49.7 ppb) followed by the summer (33.2 ppb), post-monsoon (25.8 ppb) and southwest summer monsoon season (23.7 ppb) (Fig. 13).

The Figs. 13&14 show the diurnal and seasonal pattern of gaseous pollutants over Bengaluru city in four major seasons. The diurnal variations of surface ozone concentrations were characterized by the higher concentrations during the day hours from 1000 to 1800 hrs local time: LT (varied from 59.3 to 35.7 ppb) and the lower concentration (20 ppb) during the late evening (1800 to 0600 hrs LT) and morning hours (0700 to 0900 hrs LT). After 0900 onwards, the $O_3$ concentrations is started increasing gradually just after sunrise (due to photochemical reaction) coinciding with the increasing solar radiation (SR). It was also observed that the highest concentrations (51.7 ppb) were around 1400 hrs LT thereafter it is started decreasing and maintained lower values during the entire night due to lack of sunlight. Seasonally, it was slightly different with higher concentrations during the winter and summer seasons in

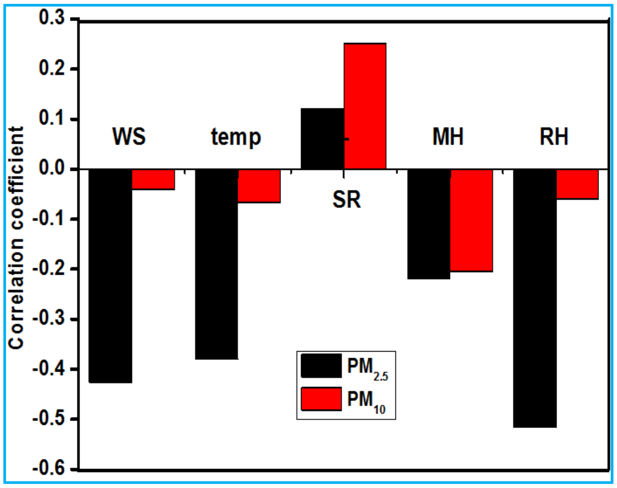


**Fig. 16.** Correlation coefficient among meteorological parameters and $PM_{2.5}$ and $PM_{10}$ over Bengaluru

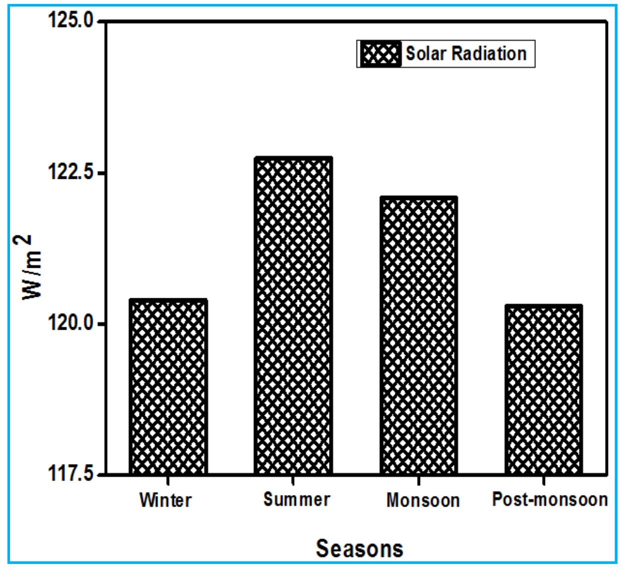


**Fig. 17.** Variation of the seasonal mean of solar radiation flux during the study period

night hours as compared to monsoon and post-monsoon seasons. Surface $O_{3,}$ which is a secondary pollutant, formed through a series of photochemical reactions among the oxides of nitrogen (NO and $NO_2$), volatile organic compounds (VOCs) carbon monoxide (CO), in the presence of intense solar radiation near the ground level. It was observed that the $NO_2$ start decreasing in day hours subsequently, $O_3$ starts increases because of its precursor and is playing a crucial role in the formation of $NO_x$.

### 3.6. *Effect of meteorological parameters on the particulate matters*

During the study period, the annual mean of wind speed (WS), temperature (Temp), relative humidity (RH) and solar radiation (SR) and mixing height (MH) were 0.70 ± 0.26 m/s, 23.3 ± 7.5 °C, 60 ± 27%, 169.1 ± 55.8 $W/m^2$ and 585.1 ± 164.6 m respectively (Fig. 15). In the present study, the dependency of both $PM_{2.5}$ and $PM_{10}$ aerosols on the local wind speed were studied and it was found that significant relationship between $PM_{2.5}$ and meteorological parameters as WS (-0.43), temperature (-0.38), mixing height (-0.22) and relative humidity (-0.55) (Fig. 16). The negative correlation among $PM_{2.5}$ and MP indicates the inverse impact of these parameters. In the cases of $PM_{10}$, it was opposite than $PM_{2.5}$ because of bigger in particle size. In addition to this, the source region was also classified through the WS on PM. The $PM_{2.5}$ and $PM_{10}$ data were separated into two WS conditions (*i*) less than 0.5 m/s (mostly calm wind condition) and (*ii*) greater than 0.5 m/s. The concentrations of $PM_{2.5}$ was ~17% higher concentrations when the WS was ≤0.5 m/s than, however, in case of $PM_{10,}$ it was opposite and was ~4% which clearly indicates that the $PM_{2.5}$ is localized as compared to $PM_{10}$ and some portion of $PM_{2.5}$ was transported from long distance over Bengaluru. The $PM_{2.5}$ mass concentrations tend to decrease with the increase in WS which is due to the impact of dilution. In the case of $PM_{10}$, increased $PM_{10}$ with the increase in WS was mainly due to wind-blown dust. Generally, during calm wind conditions, the concentrations were higher because of less dispersion of the atmospheric pollutants. During the monsoon period, the lower mass concentrations of $PM_{2.5}$ have observed it is due to the rainout mechanism that removes the atmospheric pollutants from the atmosphere and makes a clean environment favouring lower mass concentrations of PM as compared to another season.

In the case of Temp, the concentrations of $PM_{2.5}$ were significantly decreased when the temperature increased because of intensive radiative heat underlying surface area. The lower atmosphere is not very stable and turbulent strengthens, which is advantageous to the diffusion of pollutants. Therefore, the probability of atmospheric pollution decreased with the increase in air temperature in the pre-monsoon season.

### 3.7. *Effect meteorological parameters on gaseous pollutants*

The data of SR were divided annually and seasonally to see the impact of SR on the production of surface ozone by photochemical reaction. The solar radiation fluxes (direct with diffused) in clear sky condition were measured during the study period and its annual mean value was 169.09 ± 55.89 $W/m^2$ with the highest during

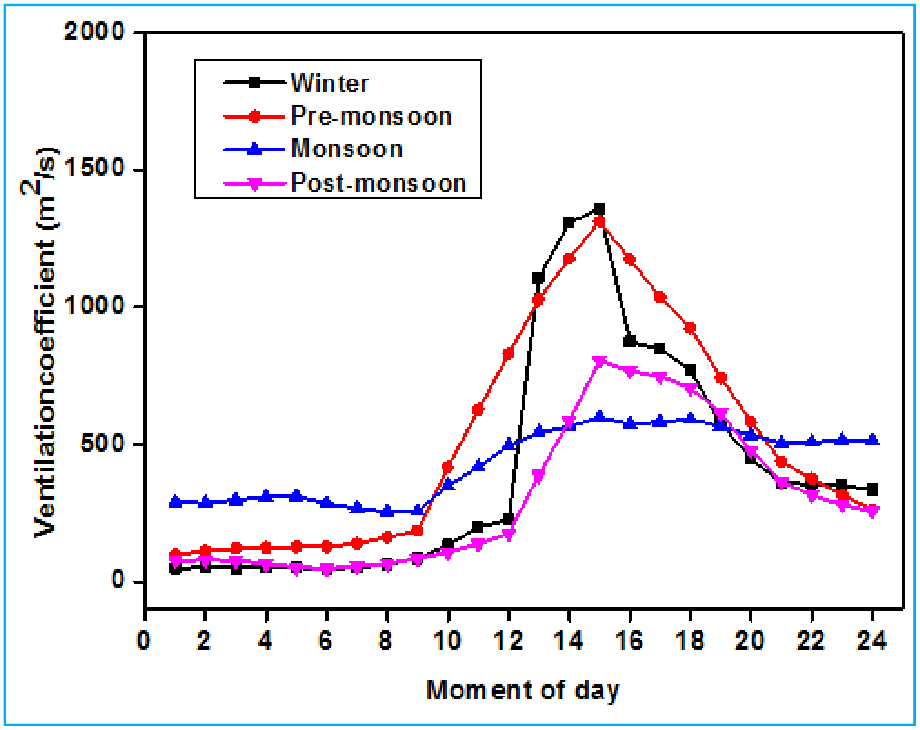


**Fig. 18.** Variations of hourly ventilation coefficient in different seasons over Bengaluru

summer months and lowest during post-monsoon months. Seasonally, it was in the order of the pre-monsoon (summer: 181.6 W/m$^2$) followed by winter (175.5 W/m$^2$), Monsoon (152.4 W/m$^2$) and Post-monsoon (142.9 W/m$^2$) seasons (Fig. 17). The highest during summer was due to higher solar radiation, however, in winter was due to the man-made aerosols. In the pre-monsoon season, the impact of SR in the formation of $O_3$ through photochemistry is confirmed, however, the higher concentrations of $O_3$ were observed higher due to biomass burning and low boundary layer along with photochemical smog reaction. The concentrations of trace gases such as Ozone, Methane, Nonmethane Hydrocarbon, ammonium, nitrogen dioxide were significantly higher during the winter and post-monsoon seasons.

### 3.8. *Vertical level variation of meteorological data with pollutants.*

Impact of ventilation coefficient (VC) and solar radiation (SR) on surface Ozone. The ventilation coefficient (VC) is a crucial parameter which provides information about dispersion and accumulation of the atmospheric pollutants in the lower atmosphere that is a product of boundary layer heights and surface wind speed. The diurnal variations of VCs in four different seasons were estimated over the Bengaluru region and depicted in Fig. 18. The hourly values of the VC indicated a similar trend in all the seasons with the highest (1935 m$^2$/s) in the summer period, however, lowest (209 m$^2$/s) was in the post-monsoon season. During the study period, the VC was highest summer season (518 m$^2$/s: annual mean) followed by monsoon (435 m$^2$/s), winter (407 m$^2$/s) and post-monsoon (306 m2/s) which is in the range of Delhi, Mumbai, and Chennai (205 to 345 m$^2$/s) in winter season, however, Kolkata (125-205 m$^2$/s) was much lower VC (Dumka *et al.*, 2020). The VC over Bengaluru were separated during the day (0800 to 1900 hrs LT) and night (1900 to 0800 to hrs LT) time and was around one and a half order of magnitude higher during daytime (587 m$^2$/s) that night (246 m$^2$/s). But seasonally, it was found a large variation during day and night as in winter (2.4 times higher during the day), summer (2.4), monsoon (0.3) and post-monsoon (1.4) season, it is due to the impact of local meteorology. Generally, the higher VC values indicate that lower pollution due to the convection and mixing pollutants, however, low VC values lead to more pollution due to accumulation.

## 4. Conclusions

(*i*) Conditional Bivariate Probability Function(CBPF) shows that, annually, the maximum concentrations of PMs over receptor sites were detected during low wind speed (< 2 knots) along the north-east direction specifying that the long-range transport does not play an essential role in the transportation of higher concentrations of PM and their primary source region may be localised.

(*ii*) Concentrated Weighted Trajectory (CWT) analysis shows that, seasonally, the highest air mass contribution of about 37% was noticed in summer, whereas the lowest was in the post-monsoon season (13%). The significant contribution of $PM_{2.5}$ transported from long distances was during monsoon, and in the case of $PM_{10}$, it was in summer. These high variations in the transported contribution of PMs are due to climatic conditions and sources of emissions. The present research investigation indicates that the $PM_{2.5}$ pollution has to be controlled to enhance the Bengaluru air quality.

(*iii*) Concentrated Weighted Trajectory (CWT) analysis was applied to find out the source region of the gaseous pollutants. During monsoon, the air masses were entirely from the southwest direction covering the Arabian sea and significant sources from the sea and two major cities as, Kannur and Mysuru, However, in post-monsoon, the airflow was from the continental side from Northwest, northeast (up to Kolkata) direction and the contribution of gaseous pollutants to the receptor site is localised. However, during summer with WS > 1m/s, the air masses were from the Northwest and easterly. It is also affected by major cities like Mumbai, Pune and Chennai, indicating that some pollutants have been transported and the remaining are localised.

(*iv*) During winter, when wind speed is greater than 5 m/s, most of the air masses arrive from the north and eastern part of India up to the Bay of Bengal, that side several commercial and industrial sites such as Chennai, Tirupati, Hyderabad, Vijayawada, Vishakhapatnam, Guntur are located, and consequences of these cities were higher concentrations of CO, NOx and $SO_2$ indicating the transfer of pollutants to the receptor site.

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**References**

Ashbaugh, L. L., Malm, W. C. and Sadeh, W. Z., 1985, "A residence time probability analysis of sulfur concentrations at Grand Canyon National Park", *Atmos. Environ*., **19**, 8, 1263-1270.

Awasthi, A., Agarwal, R., Mittal, S. K, Singh, N., Singh, K. and Gupta, P. K., 2011, "Study of size and mass distribution of particulate matter due to crop residue burning with seasonal variation in a rural area of Punjab, India", *J. Environ. Monit*., **13**, 4, 1073-1081.

Badarinath, K. V. S., Kiran Chand, T. R. and Prasad V., Krishna, 2006, "Agriculture crop residue burning in the Indo-Gangetic Plains - A study using IRS-P6 AWiFS satellite data", *Curr. Sci*., **91**, 8, 1085-1089.

Barmpadimos, I., Keller, J., Oderbolz, D., Hueglin, C. and Prévôt, A. S. H., 2012, "One decade of parallel fine ($PM_{2.5}$) and coarse ($PM_{10}$-$PM_{2.5}$) particulate matter measurements in Europe: Trends and variability", *Atmos. Chem. Phys*., **12**, 7, 3189-3203.

Charron, A. and Harrison, R. M., 2003, "Primary particle formation from vehicle emissions during exhaust dilution in the roadside atmosphere", *Atmos. Environ*., **37**, 29, 4109-4119.

Dholakia, H. H., Bhadra, D. and Garg, A., 2014, "Short-term association between ambient air pollution and mortality and modification by temperature in five Indian cities", *Atmos. Environ*., **99**, 168-174.

Draxler, R. R. and Hess, G. D., 1998, "An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition", *Australian Meteorological Magazine*, **47**, 4, 295-308.

Dumka, U. C., Gautam, A. S., Tiwari, S., Mahar, D. S., Attri, S. D., Chakrabarty, R. K., Permita, P., Hopke, Philip, K. and Hooda, R., 2020, "Evaluation of urban ozone in the Brahmaputra River Valley", *Atmospheric Pollution Research*, **11**, 3, 610-618, doi : https://doi.org/10.1016/j.apr.2019.12.013.

Hsu, Y. K., Holsen, T. M. and Hopke, P. K., 2003, "Comparison of hybrid receptor models to locate PCB sources in Chicago", *Atmos. Environ*., **37**, 4, 545-562.

Kim, E., Larson, T. V., Hopke, P. K., Slaughter, C., Sheppard, L. E. and Claiborn, C., 2003, "Source identification of $PM_{2.5}$ in an arid Northwest U.S. City by positive matrix factorization", *Atmos. Res*., **66**, 4, 291-305.

Maji, S., Ahmed, S., Siddiqui, W. A. and Ghosh, S., 2017, "Short-term effects of criteria air pollutants on daily mortality in Delhi, India", *Atmos. Environ*., **150**, 210-219.

Malby, A. R., Whyatt, J. D. and Timmis, R. J., 2013, "Conditional extraction of air-pollutant source signals from air-quality monitoring", *Atmos. Environ*., **74**, 112-122.

Sreekanth, V., Niranjan, K. and Madhavan, B. L., 2007, "Radiative forcing of black carbon over eastern India", *Geophys. Res. Lett*., **34**, 17.

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D. and Ngan, F., 2015, "HYSPLIT Publications/Meteorological Data Information", *Air Resour. Lab. Adv. Atmos. Sci. Technol. through Res*.

Sutton, M. A., Milford, C., Dragosits, U., Place, C. J., Singles, R. J., Smith, R. I., Pitcairn, C. E. R.. Fowler, D., Hill, J., ApSimon, H. M., Ross, C., Hill, R., Jarvis, S. C., Pain, B. F., Phillips, V. C., Harrison, R., Moss, D., Webb, J., Espenhahn, S. E., Lee, D. S., Hornung, M., Ullyett, J., Bull, K. R., Emmett, B. A., Lowe, J. and Wyers, G. P., 1998, "Dispersion, deposition and impacts of atmospheric ammonia: Quantifying local budgets and spatial variability", *Environmental Pollution*, **102**, SUPPL. 1, 349-361. doi : https://doi.org/10.1016/S0269-7491(98)80054-7.

Thakur, A., 2017, "Study of ambient air quality trends and analysis of contributing factors in Bangalore, India", *Orient. J. Chem*., **33**, 2, 1051-1056.

Uria-Tellaetxe, I. and Carslaw, D. C., 2014, "Conditional bivariate probability function for source identification", *Environ. Model. Softw*., **59**, 1-9.

Vreeland, H., Schauer, J. J., Russell, A. G., Marshall, J. D., Fushimi, A., Jain, G., Sethuraman, K., Verma, V., Tripathi, S. N. and Bergin, M. H., 2016, "Chemical characterisation and toxicity of particulate matter emissions from roadside trash combustion in urban India", *Atmos. Environ*., 147, 22-30.

Wen, X., Zhang, P. and Liu, D., 2018, "Spatiotemporal Variations and Influencing Factors Analysis of $PM_{2.5}$ Concentrations in Jilin Province, Northeast China", *Chinese Geographical Science*, **28**, doi : https://doi.org/10.1007/s11769-018-0992-0.