Source apportionment of PM$_{2.5}$ in North India using source-oriented air quality models$^\star$

Hao Guo$^a$, Sri Harsha Kota$^b$, Shovan Kumar Sahu$^b$, Jianlin Hu$^c$, Qi Ying$^d$, Aifang Gao$^e,f$, Hongliang Zhang$^a,c,*$

$^a$ Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
$^b$ Department of Civil Engineering, Indian Institute of Technology Guwahati, 781039, India
$^c$ Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Jiangsu Engineering Technology Research Center of Environmental Cleaning Materials, Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, School of Environmental Science and Engineering, Nanjing University of Information Science & Technology, 239 Ningliu Road, Nanjing 210044, China
$^d$ Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA
$^e$ School of Water Resources and Environment, Hebei GEO University, Shijiazhuang, Hebei Province 050031, China
$^f$ Hebei Key Laboratory of Sustained Utilization and Development of Water Resources, Shijiazhuang, Hebei Province 050031, China

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In recent years, severe pollution events were observed frequently in India especially at its capital, New Delhi. However, limited studies have been conducted to understand the sources to high pollutant concentrations for designing effective control strategies. In this work, source-oriented versions of the Community Multi-scale Air Quality (CMAQ) model with Emissions Database for Global Atmospheric Research (EDGAR) were applied to quantify the contributions of eight source types (energy, industry, residential, on-road, off-road, agriculture, open burning and dust) to fine particulate matter (PM$_{2.5}$) and its components including primary PM (PPM) and secondary inorganic aerosol (SIA) i.e. sulfate, nitrate and ammonium ions, in Delhi and three surrounding cities, Chandigarh, Lucknow and Jaipur in 2015. PM$_{2.5}$ mass is dominated by industry and residential activities (>60%). Energy (~39%) and industry (~45%) sectors contribute significantly to PPM at south of Delhi, which reach a maximum of 200 $\mu$g/m$^3$ during winter. Unlike PPM, SIA concentrations from different sources are more heterogeneous. High SIA concentrations (~25 $\mu$g/m$^3$) at south Delhi and central Uttar Pradesh were mainly attributed to energy, industry and residential sectors. Agriculture is more important for SIA than PPM and contributions of on-road and open burning to SIA are also higher than to PPM. Residential sector contributes highest to total PM$_{2.5}$ (~80 $\mu$g/m$^3$), followed by industry (~70 $\mu$g/m$^3$) in North India. Energy and agriculture contribute ~25 $\mu$g/m$^3$ and ~16 $\mu$g/m$^3$ to total PM$_{2.5}$, while SOA contributes <5 $\mu$g/m$^3$. In Delhi, industry and residential activities contribute to 80% of total PM$_{2.5}$.

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1. Introduction

Particulate matter (PM) can lead to reduced visibility (Ying et al., 2004), adversely affect human health (Pope and Dockery, 2006) and ecosystems (Qiao et al., 2015b) and change the earth’s climate by perturbing the radiation balance (Charlson et al., 1992). PM with aerodynamic diameter of 2.5 $\mu$m or less (PM$_{2.5}$) is harmful as it can penetrate into lungs and be transported by bloodstream (Atkinson et al., 2014; Bell et al., 2014; Kioumourtzoglou et al., 2016). PM$_{2.5}$ consists of primary PM (PPM), which is directly emitted into atmosphere, and secondary PM, which is formed through chemical and physical processes in atmosphere. The chemical composition of PM$_{2.5}$ is complex and typically includes elemental carbon (EC), primary organic carbon (POC), metals, sulfate (SO$_4^{2-}$), nitrate (NO$_3^-$), ammonium (NH$_4^+$), and secondary organic aerosols (SOA). Sources, chemical composition, formation, transformation and fate of PM$_{2.5}$ are quite different in different regions due to the variations in emissions and meteorological conditions (Querol et al., 2004; Shrivastava et al., 2015; Zhao et al., 2013).

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In India, the second most populous country in the world, rapid growth of industrialization and urbanization resulted in enormous increase of anthropogenic emissions. Outdoor PM ranked the seventh in causes of death in India during 1990–2010 (IHMIE, 2013). In 2010, out of 3.3 million global deaths due to outdoor PM2.5, around 0.65 million deaths were in India of which 50% were due to residential sector (Lelieveld et al., 2015). The situation in the Indian capital has been alarming with extremely high PM2.5 concentrations. For example, annual PM2.5 concentrations in New Delhi was 153 μg/m³ in 2014, more than 10 times higher than in Washington DC (WHO, 2014). Controlling PM2.5 concentrations can reduce the deaths significantly. Sahu and Kota (2017) estimated that 41 out of 100 thousand lives in Delhi could be saved by meeting the World Health Organization (WHO) suggested PM2.5 annual average standard of 10 μg/m³.

Contributions of different sources are important information for policy makers to formulate effective emission control strategies. Several source apportionment studies have been conducted in India using different methods. For example, Srivastava et al. (2008) used principal component analysis (PCA) and found that crustal re-suspension is the major proportion of heavy metals in New Delhi. Saxena et al. (2017) used PCA and concluded that secondary aerosols, soil dust and biomass burning are the major sources of water soluble inorganic ions in PM2.5 of New Delhi, and their fractional contributions are strongly dependent on seasons. Mandal et al. (2014) indicated that major parts of carbonaceous aerosols in PM2.5 in Delhi are from vehicles, coal smoke and biomass burning based on measurement of EC to OC ratios. Sharma et al. (2016) applied positive matrix factorization (PMF) model to resolve major sources of PM2.5 as secondary aerosols, soil dust, vehicle emissions, biomass burning and fossil fuel combustion in New Delhi.

Chemical transport models (CTMs) are widely used to analyze the source origins of different air pollutants. Comprehensive air quality model with extensions (CAMx), coupled with plume rise functions and hourly meteorology, has been used by Guttikunda and Jawahar (2014) to study PM2.5 related to coal-fired thermal power plants nationwide in India and it was suggested that aggressive pollution control regulations were needed. Gupta and Mohan (2013) predicted PM concentrations in New Delhi using Weather Research and Forecasting Model (WRF-Chem), and observed that emissions from North India was needed to improve the performance of the model. Marrapu et al. (2014) used WRF-Chem model to study air quality during the Commonwealth Games in October 2010 and concluded that residential emissions were the dominant source of PM2.5 in New Delhi and emissions outside New Delhi contributed to 20–50% of PM2.5 components. Source-oriented CTMs based on tagged tracer technique have been developed and used for direct source apportionment of gas (Zhang et al., 2013; Zhang and Ying, 2011a) and particulate pollutants (Kleeman et al., 2007; Ying and Kleeman, 2006; Zhang et al., 2014). For example, using the source oriented UCD/UCIT model, Zhang and Ying (2010) found that road dust, diesel engines, internal combustion engines and coal burning are the major sources for PM2.5, EC, primary organic carbon (POC) and SO₄ in Southeast Texas. Shi et al. (2017) used source-oriented CMAQ system to quantify the contributions of different sources to PM2.5 in different provinces in China. Zhang et al. (2012) used the source-oriented Community Multiscale Air Quality model (CMAQ) and observed that power generation is the important source for SO₄ and NO₃ in China. Similar analysis by Hu et al. (2015) discovered that residential/industrial emissions from local and Hebei accounted for more than 90% of PM2.5 in winter at Beijing. Although many regional air quality studies were carried out in Delhi and North India, a study using source-oriented CTMs can be a strong supplement to them.

In this paper, a source-oriented CMAQ model was applied to quantify the contributions of different source sectors to PM2.5 and its major components (PM and SIA) in North India during 2015, covering New Delhi, Chandigarh, Lucknow and Jaipur. The seasonal variations of contributions of different source sectors to total PM2.5 and its components were also analyzed.

## 2. Methodology

### 2.1. Model description

The models used in this study were based on CMAQ 5.0.1 with the SAPR1C1 photochemical mechanism and aerosol module version 6 (AERO6). The CMAQ model was modified to include heterogeneous formation of SO₄, NO₃, and SOA formation from surface uptake (Hu et al., 2016; Ying et al., 2015). Source contributions of PM and its chemical components were estimated using tagged non-reactive PMM tracers. The tracers are set to 0.001% of primary emissions from each source sector and go through all atmospheric processes same as other species. This small ratio does not significantly change particle size and mass. Then the PMM concentrations from a given source is calculated by scaling the simulated tracer concentrations from that source by 10^5, and source profiles are used to estimate PMM components concentrations using E1:

\[
C_{ij} = PMM_i \times A_{ij}
\]

where \( C_{ij} \) is component j concentration from source i, \( PMM_i \) is the concentration of total PMM from source i, and \( A_{ij} \) is the ratio of j component in PMM mass from source i. Details can be found in Hu et al. (2015) and the references therein.

The source contributions to SIA were determined by tracking SO₂, NOₓ, and NH₃ through atmospheric processing using tagged reactive tracers. Both the photochemical mechanism and aerosol module were expanded so that SO₄, NO₃, and NH₄ and their precursors from different sources are tracked separately throughout the model calculations. Reactions R1, R2, and R3 show how the nitrate formation is tracked from NO₂ reaction with hydroxyl radical (OH) in original CMAQ (R1) to source-oriented version (R2 and R3).

\[
\begin{align*}
\text{NO}_2 + \text{OH} & \rightarrow \text{HNO}_3(g) \leftrightarrow \text{NO}_3^\cdot \\
\text{NO}_2 \cdot \text{X}_1 + \text{OH} & \rightarrow \text{HNO}_3 \cdot \text{X}_1(g) \leftrightarrow \text{NO}_3 \cdot \text{X}_1 \\
\text{NO}_2 \cdot \text{X}_2 + \text{OH} & \rightarrow \text{HNO}_3 \cdot \text{X}_2(g) \leftrightarrow \text{NO}_3 \cdot \text{X}_2
\end{align*}
\]

In original CMAQ, HNO₃(g) and NO₃ are nitric acid gas and nitrate in PM.

\[
\begin{align*}
\text{NO}_2 \cdot \text{X}_1 + \text{OH} & \rightarrow \text{HNO}_3 \cdot \text{X}_1(g) \leftrightarrow \text{NO}_3 \cdot \text{X}_1 \\
\text{NO}_2 \cdot \text{X}_2 + \text{OH} & \rightarrow \text{HNO}_3 \cdot \text{X}_2(g) \leftrightarrow \text{NO}_3 \cdot \text{X}_2
\end{align*}
\]

In the source-oriented CMAQ, NO₂ is expanded to two species NO₂-X₁ and NO₂-X₂, representing the emissions from two sources. R1 is then expanded to R2 and R3. NO₃-X₁ and NO₃-X₂ represent the contributions of NO₂ from sources 1 and 2 to nitrate. Similar treatment is applied for all SIA precursors and related gas and aerosol processes. The readers are referred to previous studies for details (Qiao et al., 2015a; Zhang et al., 2014; Zhang et al., 2012). SOA prediction has large uncertainties from the emissions of its precursors, unknown formation pathways, and limited observation (Hu et al., 2017; Ying et al., 2015; Zhang and Ying, 2011b). In this

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This is a structured representation of the document, with emphasis on the key points and methods discussed. The text is formatted to highlight important models and methodologies used in the study. The document provides a comprehensive overview of the sources and processes contributing to PM2.5 in India, particularly focusing on the use of a source-oriented CMAQ model to quantify these contributions. The methodology section outlines the use of tagged PMM tracers and reactive tracers for tracking the formation of inorganic nitrate (NO₃) and organic nitrates (NO₃-X₁ and NO₃-X₂) from NO₂. The model equations and principles are elaborated, including the source contributions to PM2.5 and the methodologies used for source apportionment in India.
study, the predicted SOA contributes <7% to total PM$_{2.5}$, thus, it is treated as a separate "source type" while further studies are needed. Its source apportionment using the tagged reactive tracers is still undergoing and will be provided in future manuscripts.

2.2. Model application

Fig. 1 shows the 36-km and 12-km domains selected for the simulation in 2015 at India. The outer 36-km domain covered the whole India and several adjacent countries and the inner 12-km domain covered areas around Delhi. Generation of the meteorology and emission inputs has been described in a companion manuscript (Kota et al., 2017), and only a brief summary is described here. The Weather Research & Forecasting model (WRF) v3.7.1 was utilized to generate meteorology inputs, and the monthly emissions from Emissions Database for Global Atmospheric Research (EDGAR) version 4.3 (http://edgar.jrc.ec.europa.eu/overview.php?v=431) were used for anthropogenic emissions. The sectorial EDGAR inventories were then grouped into six broad source categories: energy, industries, residential activities, on-road transportation, off-road transportation, and agriculture (Table S1). The monthly emissions were processed to hourly level based on weekly and diurnal emission profiles specific to sources from previous studies (Olivier et al., 2003; Streets et al., 2003; Wang et al., 2010). Table S2 lists the total daily emission rates in 12-km domain of PM$_{2.5}$, EC, OC, and gaseous species. Energy and industry are the two largest anthropogenic sources of EC, while residential is the major source of OC. The top four source sectors of PM$_{2.5}$ emissions are energy (~5%), industry (~20%), residential (~55%) and agriculture (~15%), which explain 95% of total emissions. The Model for Emissions of Gases and Aerosols from Nature (MEGAN) v2.1 (Guenther et al., 2012) was used for biogenic emissions and open biomass burning emissions were generated from the Fire Inventory from NCAR (FINN), which is based on satellite observations (Wiedinmyer et al., 2011). Dust and sea salt emissions were generated in line during simulations.

The default vertical distributions of concentrations that represent clean continental conditions provided by the CMAQ model were used for 36-km domain initial and boundary conditions, and predictions in the 36-km domain provides the boundary conditions for the 12-km domain (Hogrefe et al., 2017). The impact of initial conditions was minimal as the results of the first five days were excluded. Source apportionment simulations were conducted in the 12-km domain and are presented in this paper.

The model performance for the entire year of 2015 has been evaluated in a companion paper (Kota et al., 2017) and is summarized here. Generally, the WRF model performance on key
meteorological parameters such as wind speed (WS), wind direction (WD), temperature (T) and relative humidity (RH) is generally acceptable accordingly to the criteria suggested by Emery et al. (2001) and comparable with similar studies in Asia (Hu et al., 2016). Model performance of major air pollutants including PM$_{2.5}$ also meets the criteria suggested by the US Environmental Protection Agency as shown in Table S3. Specifically, there are two stations at Delhi and Lucknow located in the 12-km domain and the model performance of PM$_{2.5}$ is shown in Fig. S1. The model prediction meets the suggested performance criteria for most months except under-prediction at Lucknow in winter.

3. Results

3.1. Source apportionment of PPM

Fig. 2 shows regional variation of annual average source contributions to PPM from eight different sources, energy, industry, residential, on-road, off-road, agriculture, open burning and dust in 2015. Energy, industry and residential sources contribute to 80% of total PPM in this domain. Dominance of energy and industrial sources is more obvious near New Delhi, Lucknow, Chandigarh, Jaipur and Lahore in Pakistan. South of Delhi is the most severely polluted among all the regions. In south Delhi, energy sector, industry and residential sources contributed to annual averaged concentrations of 25, 53 and 40 $\mu$g/m$^3$, respectively. Unlike energy and industry sectors, residential PPM is more spatially distributed and is high in Punjab, Haryana and parts of north Uttar Pradesh and East Pakistan, which have high population density. The agriculture PPM is distributed evenly in Punjab, Haryana, Delhi and parts of north Uttar Pradesh. Figs. S2 and S3, in the supplementary materials, show the contributions of different sources to EC and POC. While industry (~7 $\mu$g/m$^3$) is the largest source to EC, residential sector (~20 $\mu$g/m$^3$) is the main source for POC followed by industrial sector (~8 $\mu$g/m$^3$).

Fig. 3 shows the seasonal variations in contributions to total PPM from four source sectors of energy, industry, residential and agriculture, as the four source sectors contribute to 90% total PPM. PPM concentrations are higher at winter (December to February) followed by post-monsoon (September to November), and are lowest in monsoon (June to August) and pre-monsoon (March to May). Low emissions and enhanced wet deposition are the main reasons for the lowest PPM concentrations in monsoon, as shown in Fig. S4. The high residential PPM concentrations in winter may be due to the domestic heating in high population density areas at Punjab, Haryana, Delhi and parts of north Uttar Pradesh. Unlike the significant seasonal variation of the contributions from residential sector, contributions from energy and industry sector are relatively steady among different seasons. Agricultural PPM emissions are the highest during pre-monsoon due to the residual burning (Awasthi...
et al., 2010; Pandey et al., 2014). However, the agricultural PPM concentrations are highest in winter indicating the importance of meteorology in this region. The seasonal variations in source contribution of EC and POC (shown in Figs. S5 and S6) have very similar trend to total PPM.

Source apportionment of PPM in Delhi and three surrounding cities, Chandigarh, Lucknow and Jaipur are shown in Fig. 4 and Fig. S7. Higher PPM concentrations are found in Delhi compared to other three cities. Residential sources are the dominant contributor to PPM in all cities. In Lucknow, Jaipur, Chandigarh and Delhi, residential sources contribute to 67, 57, 57 and 44%, respectively, to average PPM in 2015. Industries contribute to 47, 18, 31 and 20%, respectively, in Delhi, Chandigarh, Jaipur and Lucknow. While energy is the third most important source in Delhi, agriculture is more important in the other three cities. The greatest contribution of agriculture to PPM is in Chandigarh (17%). On-road PPM is at least twice off-road PPM on all seasons in Delhi, and the two sources are similar in the other cities. Although similar seasonal trends are found in all these four cities, the contributions of sources to PPM are different. The energy, industry and residential sectors at all cities are maximum during post-monsoon and winter and least during monsoon. Highest daily PPM concentrations in Delhi, Lucknow, Chandigarh and Jaipur are 220, 92, 62 and 46 μg/m³, respectively. Contributions of industrial and residential sectors on days with highest PPM concentrations in Delhi, Lucknow, Chandigarh and Jaipur are 88, 90, 70 and 84%, respectively. Agricultural residue burning in India happens during October—November and April—May (Awasthi et al., 2010; Pandey et al., 2014). Unlike energy, residential and industrial PPM, which has higher concentrations in December than October—November, higher agriculture PPM is observed in North India in winter. Large agriculture contribution is observed across the year in Chandigarh in Fig. 4 and Fig. S7. The contribution of dust emissions is the highest in monsoon and the least in winter at all the cities. In Delhi, Lucknow, Jaipur and

Fig. 4. Daily contributions of PPM at New Delhi, Chandigarh, Jaipur and Lucknow cities from (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning and (h) dust. Units are μg/m³.
Chandigarh, dust emissions contributed much higher to PPM in monsoon than in winter. The maximum contribution of dust emissions to PPM (84%) is observed at Jaipur, which is in close proximity to Thar Desert. This region experiences dust-storms, thunderstorms and dust raising winds during the hot wet season, which brings high dust contributions. It could also due to uncertainties in WRF predicted soil moisture used for dust emissions estimation in East Asia as reported in a previous study (Darmenova et al., 2009).

3.2. Source apportionment of SIA

Previous studies indicate that SIA account for a significant fraction of total PM$_{2.5}$ (Wang et al., 2014; Zhang et al., 2012). Fig. 5 shows the annual averaged regional contribution of each source to SIA in the 12-km domain. Similar to PPM, energy, industry, residential and agriculture are the major source sectors for SIA. However, unlike PPM, SIA concentrations from different sources are more distributed due to their secondary nature. High SIA concentrations (~30 $\mu$g/m$^3$) are observed at south of Delhi and central Uttar Pradesh in sectors of energy, industry and residential, while Punjab, Haryana, and parts of north Uttar Pradesh have a relatively lower SIA concentration (~10 $\mu$g/m$^3$) in these three categories. Agriculture SIA is distributed evenly along Punjab, Haryana, Delhi and north Uttar Pradesh. Overall, from Figs. 2 and 5, relative contributions of agriculture emissions to SIA is higher than their contributions to PPM as the major of agriculture emission are NH$_3$ and NO$_2$ which are precursors to NH$_4$ and NO$_3$ in SIA (Paulot and Jacob, 2014).

As Fig. S8 shows, energy is the dominant source of nitrate. Nitrate concentrations from energy production (~2 $\mu$g/m$^3$) are concentrated at south of Delhi as several coal-based power plants located there (Guttikunda and Jawahar, 2014; Prasad et al., 2006). Moreover, the contribution of on-road sources to nitrate is also significant. Also, energy is the major source of sulfate as shown in Fig. S9, and agriculture is the major source of ammonium ion as shown in Fig. S10. As the dust sector has no gaseous precursor emissions, it does not contribute to sulfate and ammonium ion and thus is not shown in Figs. S9 and S10. Overall, it can be concluded that control of energy and agriculture sources is expected to be effective for reducing SIA and its components in this region.

Fig. 6 presents seasonal variation of SIA concentrations based on the top four source sectors: energy, industry, residential and agriculture. Similar to PPM, SIA concentrations are higher in winter than in other seasons because of higher emission resulting from residential heating in winter and unfavorable meteorological conditions for dispersion of pollutants as reported by previous studies (Kulshrestha et al., 1995; Norman et al., 2001). Industrial and residential sectors have the peak concentration (~5 $\mu$g/m$^3$) at south of Delhi in winter while high concentration occurs along Punjab to North Uttar Pradesh in winter for energy and agriculture sector (~6 $\mu$g/m$^3$). Fig. S11 shows seasonal variation of nitrate concentrations from these sectors. Compared to total SIA, nitrate has more significant seasonal variation as the extreme low concentrations are observed in monsoon season from all these sectors. However, the peak values still occur in winter along Punjab to north Uttar Pradesh. Energy and industry sectors have higher sulfate concentrations in pre-monsoon and monsoon at central Uttar Pradesh as observed in Fig. S12. Residential and agriculture sectors do not have observable seasonal variations. The seasonal variation of ammonium ion is quite similar to that of nitrate and sulfate, even though there are significant point sources in energy and industry sectors and the major source of ammonium (agriculture) is more distributed as shown in Fig. S13.
Fig. 7 and Fig. S14 shows source apportionment of SIA in Delhi, Chandigarh, Lucknow and Jaipur. Higher SIA is found in Delhi, followed by Lucknow, Chandigarh and Jaipur. While energy sector is the main contributor to SIA in Delhi and Jaipur, agriculture is the main source of SIA in Chandigarh and Lucknow. Energy and residential sources together contribute to 45, 65, 61 and 55% of SIA in Delhi, Chandigarh, Jaipur and Lucknow, respectively. Unlike other cities, in Delhi, industry and residential sources are more important than agriculture. The relative contribution of on-road and open burning sources is more significant for SIA than PPM. Chandigarh had highest contributions from open burning, i.e. 1.57%. Contribution of SIA from agriculture is higher during biomass burning seasons, i.e. April–May and October–November, in all cities. Among industrial, residential and energy sources, while energy sources dominate during pre-monsoon and monsoon, contribution of residential sources to total SIA is maximum in winter and post-monsoon. On-road SIA reaches the highest concentrations in winter, with maximum contributions being 20, 32, 29 and 53%, respectively.

3.3. Source apportionment of total PM$_{2.5}$

PPM and SIA are the two major components of total PM$_{2.5}$ in India (Kota et al., 2017). Fig. 8 shows the annual contributions of different sources and SOA to total PM$_{2.5}$. Residential sector contributes highest to total PM$_{2.5}$ about –80 µg/m$^3$, followed by industry sector (~70 µg/m$^3$). Energy sectors and agriculture sector contribute to ~25 µg/m$^3$ and ~16 µg/m$^3$. Energy and industry concentrations have a significant high concentration point at south of Delhi and its surroundings. On the contrary, SOA, residential and agriculture sector distributed evenly at Indo-Gangetic plain. Additionally, residential sources also peaked in north-Pakistan. Fig. 9 shows the contributions of different sources to PM$_{2.5}$ total mass at selected four cities. Generally, residential sector contributes the most to total PM$_{2.5}$ followed by industry, energy and agriculture sectors. Energy, residential and industry sources contribute to at least 75% of total PM$_{2.5}$ in all the cities. Contribution of SOA is maximum in Jaipur, 7%, and least in Delhi, 3%. Fig. S15 shows the comparison of the relative source contributions to PM$_{2.5}$ at Delhi using PMF model for 2013–2014 (Sharma et al., 2016) and the source-oriented CMAQ model in the present study for 2015. To be consistent, sources in the present study e.g., residential, energy and agriculture were further reclassified as biomass and fossil fuel in Table S4 using the energy consumption data provided by the Indian government (www.indiaenvironmentportal.org.in/files/file/pngstat.pdf). The source contributions estimated by these two methods are generally consistent at Delhi except for traffic and biomass burning categories. The difference may be due to coarse
grid (12-km) of emission used in our study and uncertainties contained in PMF model used in Sharma et al. (2016). According to another study (Chowdhury et al., 2007), fossil fuel combustion is responsible for about 25–33% of PM$_{2.5}$ mass in Delhi, and 28% in Chandigarh, which is consistent with our results: 20.7% in Delhi and 23.2% in Chandigarh. The agreement with other studies at different cities shows the reliability of the source apportionment results of this study.

4. Conclusion

A source-oriented CMAQ modeling system driven by the off-line meteorological inputs from the WRF model was used to quantify the major source contributions to primary, secondary inorganic and total PM$_{2.5}$ in Delhi and surrounding cities in North India in 2015. This study finds that industrial and residential activities are the dominating sources (60–70%) for EC and POC, while energy and agriculture are also important sources to SIA and its components i.e. nitrate and sulfate. The spatial distribution of energy and industry sectors shows significant point sources at south of Delhi in both PPM and SIA source apportionment analysis while residential and agriculture sectors are distributed evenly in the Indo-Gangetic plain. A strong seasonal variation in the sectors’ contribution to PPM and SIA is also predicted. In most areas, the peak concentration

Fig. 7. Daily contributions of different sectors to SIA at specific cities from source types (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture (g) open burning and (h) dust. Units are $\mu$g/m$^3$. 
is observed at winter followed by post-monsoon and pre-monsoon seasons and lowest at monsoon in all sources. All the selected cities are all facing severe PM$_{2.5}$ pollution during winter. PPM concentration can reach ~200 μg/m$^3$ at Delhi. Contributions of agriculture to PPM and SIA were higher during October—November coinciding with the residual burning. Industry, residential and energy are the three major sources to PM$_{2.5}$ in all the cities. The variation in the seasonal, spatial and source sector contributions emphasizes the importance of a better understanding the sources of PPM, SIA and its components when designing efficient regional emission control strategies towards reducing severe air pollution issues occurs at Delhi. Future studies should be carried out to better interpolate the results of this study, including obtaining source apportionment of SOA in this region, conducting correction for the bias error (Solazzo et al., 2017), and considering feedbacks of aerosols on meteorology using online coupled source-oriented models in future (Im et al., 2015).

Fig. 8. Total PM$_{2.5}$ source apportionment in 12-km domain from source types (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, (h) dust and (i) SOA concentrations. Units are μg/m$^3$.

Fig. 9. Contributions of different source sectors to total PM$_{2.5}$ at selected cities.