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A Review of Air Quality Modeling Studies in India: Local and Regional Scale

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Abstract

Developing countries like India require proper control strategies for reducing the enormous premature mortality associated with air pollution. Air quality models, in addition to helping to understand the severity of air pollution by providing the pollutant concentrations, also give knowledge of the sources. Previous local and regional air quality modeling studies carried out in India are reviewed in this current study with a goal of understanding the current gaps and exploring future directions. Studies carried out in different parts of India during past decade were precisely documented in this study using methodical Scopus, Web of Science, and Google searches. Majority of the air quality studies are concentrated in megacities leaving behind the small cities which require greater attention in future. While most of the modeling studies were carried out in northern India, very few studies concentrated on central region of the country. Review of both local and regional numerical models showed the need for better emission inputs, while the statistical models inferred the need for proper selection of key tracers for source allocation. Irrespective of emission inventory and models used, particulate matter concentrations are under predicted in Delhi, which faces huge air pollution-related issues. Dust and traffic emissions are the major sources of particulate matter in India.

Keywords India · PMF · CMAQ · AERMOD · PM2.5 · Toxic pollutants · VOCs

Introduction

Over the decades, high population growth has triggered rapid industrialization, urbanization, and increase in vehicular traffic that has led to deterioration of air quality. Furthermore, the lack of strict implementation of environmental regulations has only added to the pollution woes in developing countries like India. According to the World Health Organization (WHO) [1] in 2016, half of the top 20 polluted cities are in India. In order to monitor the air pollution trends, Central Pollution Control Board (CPCB) has set up 591 monitoring stations around the country covering 248 cities/towns in 28 states and 5 union territories [2]. In 2015, for example, averaged concentrations of SO_2 and NO_2 in major cities did not exceed National Ambient Air Quality Standards (NAAQS) in any of the major cities in India. In contrary, the annual average concentration of $PM_{2.5}$ in major cities in north, east, west, and south Indian cities were 3.3, 3.7, 2.3, and 1.6 times of NAAQS standard (40 $\mu g/m^3$). Even the 8-h concentrations of O_3 and CO in major cities in north (47.8 and 1.26 mg/m^3), east (48.1 and 1.73 mg/m^3), west (58.6 and 1.27 mg/m^3), and south India (58.6 and 0.94 mg/m^3) were less than the NAAQS standards (100 and 2 mg/m^3) [3]. Exceedance of pollutant concentrations can primarily be attributed to dust emissions, vehicular emissions, biomass burning etc. [4]. Aggravated concentrations of criteria pollutants pose constant threat to human health and environment. India accounted for 25.7% of global premature deaths due to $PM_{2.5}$ exposure in the year 2015 [5]. $PM_{2.5}$ concentrations exceeding WHO set limits resulted in 6.5% excess mortality in the Indian capital [6].

Many of the high- and middle-income group countries have extensive network of monitoring stations covering most of rural and urban areas, which provide continuous measurements of pollutants (for example, see [7, 8]). Setting up of a network of monitoring stations in developing countries like India is not economically viable. Since continuous monitoring of air pollutants is of prime importance in India where air pollution levels are among one of the world's highest [5],

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other methods such as data from satellites [9, 10] and air quality models are used to estimate pollutant concentration in such cases. Moreover, sparse spatial coverage of monitoring stations limits their use and hence air quality models are used to obtain the spatial and temporal variations of pollutant concentrations. On the basis of spatial resolution, air quality models can be divided into (i) local, (ii) regional, (iii) global/meso scale models. Models with a domain size of few meters to few km are termed as local/urban scale (for example, see [11]), tens of km to hundreds of km are treated as regional models (for example, see [12, 13]). All the models coarser than regional models are treated as global/meso scale models [14]. A sensitivity study using a regional photochemical model of ozone in local/urban scale to regional ozone episodes indicated that increase in ozone levels in local/urban zones were related to increase in ozone in regional scale [15]. Thus, pollutants released locally can affect regional air quality.

Local air quality modeling studies provide critical information regarding the status of air quality in our vicinity. A three-dimensional Eulerian model [16] was used to simulate dispersion of near road gaseous air pollutants using on road emissions [11]. Source contributions of volatile organic compound fluxes in a city were carried out using a receptor model [17]. Regional models have a greater spatial coverage and help in predicting concentrations or identifying sources at a much wider scale. A 7-year air quality simulation in eastern USA [7] revealed that while O_3 and PM_{10} were modeled satisfactorily, $PM_{2.5}$ and its components were slightly over-predicted. Similarly, a yearlong simulation of ozone and particulate matter in China [18] revealed over prediction of O_3 at low concentration ranges, and under prediction of $PM_{2.5}$ during summer. Source apportionment studies using source oriented regional air quality models enable one to obtain contributions from sources without being limited by the frequency and spatial coverage of observations. These studies are often used to validate emission inventory of pollutants [19]. A study [13] indicated significant contribution of isoprene to secondary organic aerosol (SOA) in eastern USA during summer. A source apportionment study of particulate matter in China [20] using source oriented air quality model revealed residential and industrial emissions to be chief contributors to primary $PM_{2.5}$, and industries, agriculture, power plants, and transportation were important sources to secondary aerosols. However, only one such study was carried out in India [21].

Many air quality-modeling studies, around the world, in the past have been carried out at both local and regional scale for various applications. It is important to combine and evaluate the results from the studies of different scales to achieve better understanding of the model performance. For example, an overview of modeling practices in European Union (EU) revealed that no single model is currently capable to accurately predict air quality at all spatial scales, with emissions carrying the most uncertainty among inputs [22]. Such reviews can also aid in identifying possible mitigation strategies. For example, a study reviewing ozone modeling studies around the world have revealed over-estimation of night time ground level ozone (GLO), greater influence of NOx over VOCs in export of ozone from urban region, better performance of fine resolution inputs, and greater contribution of temperature rise and biogenic VOC to GLO concentration [23].

Moreover, a review of modeling studies carried out in a particular scale in a country/region can also aid in better understanding of the sources in the entire region. For example, a recent review [24] on source apportionment (SA) studies carried out in China shows that while South China is categorized by higher contributions of vehicle exhaust and secondary sources, dust, coal combustion, and biomass burning are the leading sources in North China. A European study [25] which reviewed the published literature using meta-analysis found that sea salt, dust, traffic, point sources, and biomass burning are the constantly reported sources in different European cities. While in India, SA of airborne particulates was thoroughly reviewed [26] and concluded that dust emissions as the principal source followed by traffic emissions, industrial emissions, coal combustion, sea salt, and biomass burning are the most commonly apportioned sources.

Most of the reviews of modeling studies in India are either on a single pollutant (for example, see [27]) or constrained to a single scale (for example, see [28]). Therefore, the goal of the present study is to provide a comprehensive review of all local and regional scale modeling studies carried out in different parts on various pollutants in India. For this purpose, the studies have been divided into regional scale and local scale, based on the domain size. Therefore, this study will not only aid in understanding the current knowledge gaps, but also help in providing proper control strategies in India, which is currently facing severe air pollution-related issues.

Study Design

Metadata reported by the air quality modeling studies carried out throughout India on PM, VOCs, PAHs, O_3, SO_2, NO_2, NO_x, and Black Carbon (BC) were reported in this study. For the present study, each article published in a peer-reviewed journal was logically searched using database from Scopus, Web of Science, and Google searches. Table 1 depicts the number of studies covered in different regions using different models in India. It shows that Northern India has been extensively studied with Central India being the least studied region. Overall, 130 research publications during past 5–7 years were thoroughly inspected. Of the studies collected, 60 local and 35 regional studies conducted in five different regions, i.e., north, south, east, west, and central parts of India were used.

Table 1 Total number of studies with respect to different models in regional and local scale distributed all over India

Scale	Region	No. of studies	WRF-Chem		MOZART		WRF-CAMx		Others
Regional	North	17	9		3		2		a, b, c, d, e
	East	11	6		2		1		b, c, d
	West	10	1		5		2		a
	South	15	6		4		2		b, c, d, e
	Central	1	1		-		–		d
	Region	No. of studies	PCA	PMF	CMB	CALINE	ISCST3	AERMOD	Others
Local	North	22	9	3	1	2	3	3	f, g, h, i
	East	9	4	1	1	1	1	–	k, l
	West	14	1	4	1	–	–	2	j, p, q
	South	14	–	5	1	–	3	2	j, m, n, o
	Central	3	2	–	–	–	–	–	j

[a] RegCM
[b] GOCART
[c] CHIMERE
[d] SPRINTARS
[e] CMAQ
[f] IITLS
[g] ADMS
[h] SPM
[i] GFLSM
[j] ATMOS
[k] M-GFLSM
[l] CAL3QHC
[m] FDM
[n] CBM
[o] GPM
[p] OSPM
[q] USM
[r] UNMIX
[s] EF

Regional Scale

The current review attempted to include studies which used regional models for predicting pollutant concentrations. Studies with models predicting surface concentrations of pollutants were only included for the analysis. Moreover, studies which explicitly mention model performance or at least had a plot of observed and predicted concentrations were only considered. The following are some of the most generally used regional models in India: Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem), Model for Ozone and Related chemical Tracers (MOZART), Community Multiscale Air Quality Model (CMAQ), and Comprehensive Air Quality Model with extensions (CAMx). Since model specific work in India has only gained momentum in recent years, to include diverse set of models, all available studies were included. The regions were further grouped into urban and semi-urban areas based on their population as provided in http://www.newgeography.com/content/002537-urbanizing-india-the-2011-census-shows-slowing-growth.

The search keywords used for regional studies were as follows: air quality model in India, air quality model in Delhi, Patna, and likewise in different cities; air quality model in north, south, east, and central India. Also, the model name followed by city name were used as keywords, i.e., CMAQ Delhi, CMAQ Mumbai, CMAQ Kolkata, CMAQ Kanpur, CMAQ Bangalore, CMAQ Chennai, and likewise, similar searches were done using WRF-Chem, CMAx, and MOZART.

As majority of the studies reported predicted and observed values in the form of plots, to extract the data, Webplotdigitizer software (https://automeris.io/WebPlotDigitizer/) was used. The software is easy to use and provides both manual and automatic point selection modes to easily identify points on the plot, which can be downloaded in the form of a csv file.

Model performance is generally estimated using mean fractional bias (MFB), mean normalized bias (MNB), mean fractional error (MFE), mean normalized error (MNE), factor of 2 (FAC2), correlation coefficient (R), etc. [29]. However, as different studies use only one or a few of the above mentioned statistics, it is tough to compare model performance of each individual study. This study used a simpler approach by evaluating the ratio of predicted and observed concentrations. Ratio between 0.80 and 1.20 were considered as satisfactory model performance.

Local Scale

In this study, based on model formulation, the local studies have been divided into two categories viz. statistical and numerical models.

Local Statistical Modeling Studies

Receptor oriented source apportionment (RSA) models are commonly used statistical models to obtain the source contributions of the measured pollutant in a region. Keywords used for SA studies were source apportionment, receptor models, PM_{10} and $PM_{2.5}$, VOCs and PAHs.

Some of the commonly used RSA techniques in different Indian studies were as follows: enrichment factor (EF) (34%), principal component analysis (PCA) (36%), positive matrix factorization (PMF) (15%), UNMIX (3%), and chemical mass balance (CMB) (10%) [27].

Most of the RSA studies in India are carried out to identify the sources and their contributions to measured PM, VOCs, and PAHs. Identification of key tracer species for each source is one of the chief steps in source allocation. Although there is ambiguity, as reported by earlier reviews [27, 30–32], in finding the tracers, based on the commonly reported sources in different RSA studies, seven common source categories were considered in this study: traffic, biomass burning, coal combustion, industry, sea salt, dust, and other sources.

(i) Traffic: This includes on-road emissions related to motor vehicles, i.e., tail pipe, non-tail pipe, brake wear, and tire wear.
(ii) Biomass burning: Emissions from burning of biomass, wood, vegetative burning, etc., which are used for cooking and heating.
(iii) Coal combustion: Emissions from mining activities and burning of coal.
(iv) Industry: This group contains the mixture of emissions mainly from power plants and all the various types of industries.
(v) Sea salt: Sea salt and ship emissions.
(vi) Dust: This category includes emissions from re-suspended dust, earth's crust, and other soil emissions.
(vii) Other sources: All other anthropogenic emissions, including contributions of secondary organic aerosols.

Local Numerical Modeling Studies

Study design follows the similar procedure described in the regional modeling section. The search keywords used for the studies were similar to regional studies but with the inclusion of different model names such as AERMOD, CALINE, and ISCST.

Results and Discussions

Regional Scale

Studies were divided into urban and semi-urban regions. Figure 1a shows the ratio of predicted to observed concentrations. The results of those studies are described in detail below:

Northern India

Urban

A study simulated PM_{10} concentrations using WRF-Chem in Delhi with 3.3-km resolution domain using Emission Database for Global Atmospheric Research (EDGAR) emission inventory [33]. Results indicated that the predicted to observed ratio (P/O) increased with the domain size, as the domain size was progressively increased from Delhi region (P/O = 0.12) and so on to North India (P/O = 0.57) and then to whole Asia region (P/O = 0.74). Similarly, another study predicted $PM_{2.5}$ concentrations using WRF-Chem with 20-km resolution and emissions from EDGAR emission inventory [34]. The model performance at two cities, i.e., Agra (P/O = 0.83) and Delhi (P/O = 0.94), was satisfactory. CHIMERE and Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) models were used to simulate aerosol over the Indian subcontinent at a resolution of 111 km [28] with the former using EDGAR emission inventory and the later using a pre-compiled emission inventory [35]. The predicted concentrations for both models were lower than the observations in Delhi with P/O = 0.64 and 0.22 using CHIMERE and GOCART models, respectively. In another study, BC was simulated using WRF-Chem at 12-km horizontal resolution and Spectral Radiation Transport Model for Aerosol Species (SPRINTARS) at 1.125°

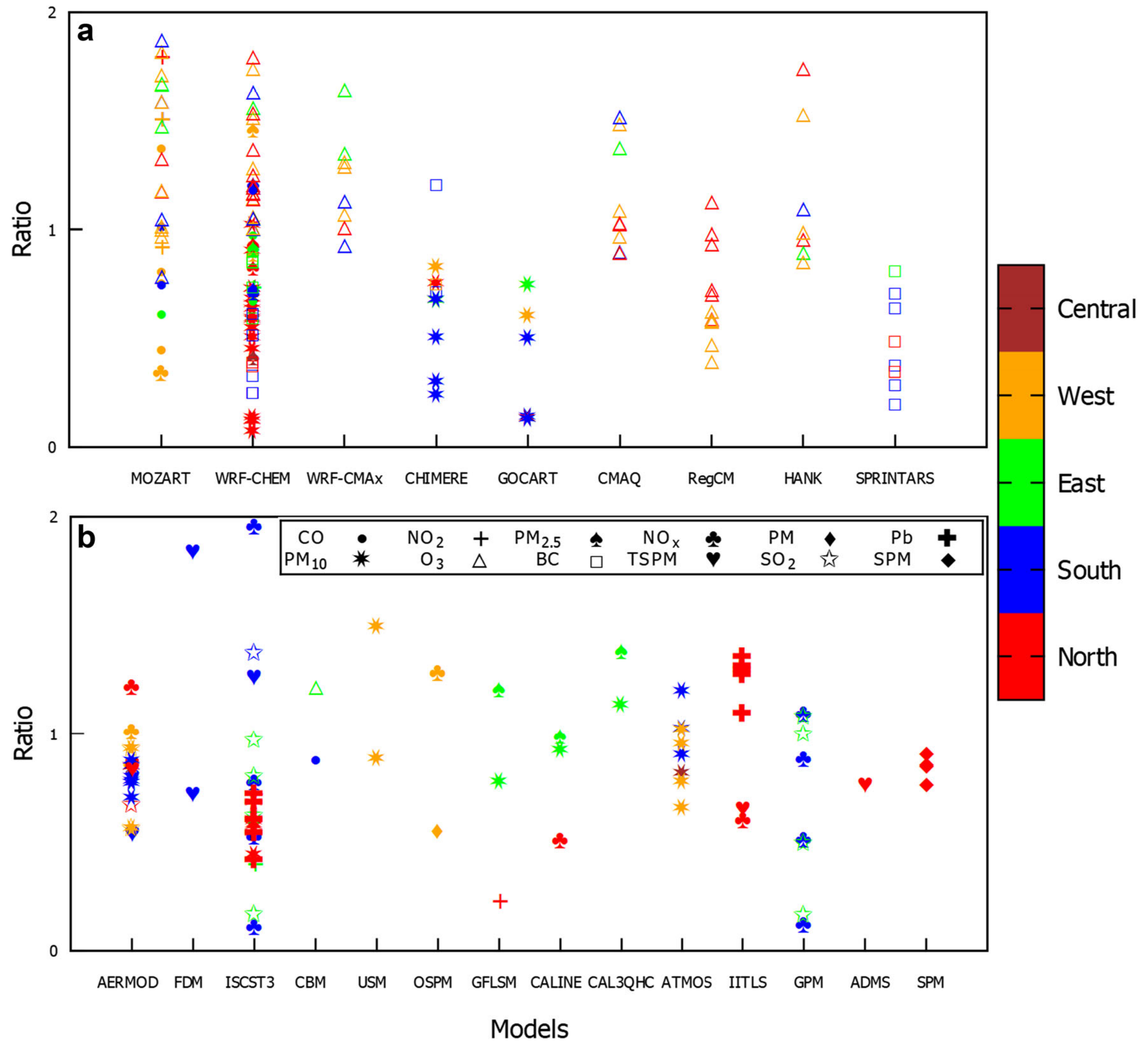

Fig. 1 Ratio of predicted to observed concentrations of **a** regional and **b** local models. While the point shape indicates pollutant types, the color indicates the region where the study has been undertaken

resolution with emission inputs from an emission inventory compiled using reanalysis of tropospheric chemical composition (RETRO) and for the former, and using RCP8.5 emission inventory for the later [36]. Both models under predicted BC concentration at Delhi (P/O = 0.409 and P/O = 0.505) and Varanasi (P/O = 0.39 and P/O = 0.363). Regional climate model was used by some studies to determine BC concentrations using optical properties of the model at a horizontal resolution of 30 km [37]. Observations from two urban city centers when compared with predictions were found to be good in Kanpur (P/O = 1.02) with under predictions in Delhi (P/O = 0.68). In an another study, the simulated NO_2 concentrations, from Model for Ozone and Related chemical Tracers (MOZART) at 2.8° horizontal resolution with emission inputs from Precursors of Ozone and their Effect on the Troposphere (POET) [38], in a northern urban center were higher than observations (P/O = 1.8). Another study in Delhi was conducted using WRF-Chem model with EDGAR emission inventory at 10-km resolution [39]. Two chemical mechanisms were used for the analysis of O_3: carbon bond mechanism (CBMZ) and regional atmospheric chemical model (RACM), results indicated that simulation using CBMZ (P/O = 1.29) performed better than RACM (P/O = 1.42).

Semi-Urban

A study used CHIMERE and GOCART for simulating aerosol over the Indian subcontinent at a resolution of 111 km [28], using EDGAR and pre-compiled emission inventory, respectively. Comparison of model predictions with observations in a semi-urban area revealed under prediction, i.e., P/O = 0.76 and 0.13 by both CHIMERE and GOCART, respectively. WRF-CAMx predicted non-methane VOCs (NMVOC) concentrations, using an in situ emission inventory with 25-km horizontal grid resolution [40], at two semi-urban areas were closer to observed concentrations except in areas with limited observation data. An in situ emission inventory at 36-km resolution was input to WRF-CMAQ to simulate concentration over India [41]. The model performance was good at Nainital (P/O = 1.04) and indicated slightly over predictions in Gandaki (P/O = 1.38). Similarly, CMAQ was used to simulate tropospheric ozone over south and East Asia with horizontal resolution of 60 km and in situ emission data. Comparison with observed data revealed that the model performed satisfactorily (P/O = 1.04). In another study, WRF-Chem and MOZART were used for simulating tropospheric ozone over India with resolutions of 45 km and 2.8°, respectively, using INTEX-B and RETRO emission inventories [42]. The model performance of MOZART and WRF-Chem were found to be good in one location (P/O = 1.18 for both models), and over predicting at another (P/O = 1.7 and 1.6). A study simulated O_3 over India using WRF-Chem with a spatial resolution of 30 km [43]. The performance of the model was found to be satisfactory at a semi-urban area, P/O = 0.87 and 1.08 using INTEX-B and HTAP-v2 emission inventories, respectively.

Eastern India

Urban

Simulated BC using WRF-Chem at 12-km horizontal resolution and emission inventory compiled using RETRO and EDGAR, and SPRINTARS at 1.125° resolution with emissions from RCP8.5 [36] resulted in satisfactorily performance (P/O = 0.884 and P/O = 0.826, WRF-Chem and SPRINTARS, respectively).

Semi-Urban

WRF-Chem was used to simulate BC concentrations at a spatial resolution of 0.25° with emissions from EDGAR [44]. Evaluation of model performance revealed under prediction at Agartala (P/O = 0.61) and Dibrugarh (P/O = 0.75) and satisfactory in Imphal (P/O = 0.87) and Shillong (P/O = 0.86). Similarly, MOZART with emission inputs from HTAP-v2 was used to model ozone and related tracers at a resolution of 1.9° × 2.5° [45]. Apart from CO, other species were over predicted. Predicted BC concentrations using CHIMERE with EDGAR emissions and GOCART with precompiled emissions at a horizontal resolution of 111 km [28, 35] indicated under predictions (P/O = 0.68 (CHIMERE) and P/O = 0.75 (GOCART)). The concentrations were over predicting in a semi-urban site (P/O = 3.07). In another study, WRF-Chem simulated $PM_{2.5}$ concentration over the Indian subcontinent at 20-km horizontal resolution and emission inputs from EDGAR emission inventory [34]. The predicted concentrations were satisfactory when compared to observations (P/O = 0.92). A study simulated NMVOC concentrations at 25-km horizontal grid resolution using WRF-CMAx with in situ emission inputs [40]. The model over predicted O_3 concentrations at a semi-urban site (P/O = 1.36). WRF-Chem was used to simulate O_3 concentration in South Asia using INTEX-B emission inventory at 0.5° grid resolution [46]. The model without fire emissions showed under predictions for CO (P/O = 0.67) and NO_2 (P/O = 0.74) and over prediction of NO_2 (P/O = 2.42) and good performance of CO (P/O = 0.98) when fire emissions were included.

Western India

Urban

$PM_{2.5}$ simulation was performed using WRF-Chem with EDGAR emission inventory at 20-km horizontal resolution [34]. Model was found to satisfactorily predict $PM_{2.5}$ concentrations (P/O = 0.89). Predicted BC concentrations at 30-km horizontal resolution using a regional climate model were lower than observations at Ahmedabad (P/O = 0.54) and Pune (P/O = 0.55) [37]. In another study, MOZART predicted NO_2 concentrations, at a horizontal resolution of 2.8° resolution with emissions from POET, were higher than observations at Pune (P/O = 1.5) and closer to observation at Ahmedabad (P/O = 0.93) [38]. NMVOC simulation over India using WRF-CMAx with an in situ emission inventory at 25-km horizontal grid resolution [40], slightly over predicted O_3 concentration at Ahmedabad (P/O = 1.3). A study simulated O_3 and its precursors using CMAQ and MOZART at 60-km resolution with emission inputs from an in situ emission inventory [47]. The predicted concentrations by both models were satisfactory. In an another study, MOZART was used to simulate O_3 and its precursors with a resolution of 1.9° × 2.5° using HTAPv2 emission inventory [45]. The predicted CO values were found to be slightly lower than observations in Pune (P/O = 0.76), while they were closer to observations in Udaipur (P/O = 0.81). Similarly, MOZART was used to model ozone and its precursors using POET emission inventory at a resolution of 1.8° [48]. The model showed satisfactory performance for O_3 (P/O = 1.16), under predictions for CO (P/O = 0.45) and NOx (P/O = 0.35).

Semi-Urban

Simulated O_3 using WRF-CMAx and an in situ emission inventory with 25-km horizontal grid resolution [40] showed satisfactory model performance (P/O = 1.08).

Southern India

Urban

WRF-Chem simulated $PM_{2.5}$ using EDGAR emission inventory at 20-km horizontal resolution [34] showed under predictions at Chennai (P/O = 0.73) and Hyderabad (P/O = 0.72). CHIMERE and GOCART were used to simulate BC concentration at 111-km horizontal resolution [28] using EDGAR and precompiled emission inventories, respectively [35]. Both these models under predict concentrations at Hyderabad (P/O = 0.30 and 0.15) and Thiruvananthapuram (P/O = 0.68 and 0.50). Another study used WRF-Chem at 12-km horizontal resolution and SPRINTARS at 1.125° resolution with emissions from a precompiled emission inventory and RCP8.5, respectively [36]. The model performance indicated under predictions at four cities. MOZART predicted NO_2 concentration at a horizontal resolution of 2.8° resolution with emission inputs from POET [38] were higher than observations at Bangalore (P/O = 1.5). In another study, MOZART was used to simulate ozone and its precursors with a horizontal resolution of 1.9° × 2.5° using HTAP-v2 emissions [45]. The model under predicted CO at Chennai (P/O = 0.75).

Semi-Urban

WRF-Chem was used to simulate $PM_{2.5}$ concentrations at 20-km horizontal resolution with EDGAR emission inventory [34]. Model slightly over predicted concentrations (P/O = 1.21). Predicted BC using CHIMERE and GOCART [28] at 111-km resolution with emissions from EDGAR and precompiled BC emission inventory [35] were significantly lower than observed concentrations at two semi-urban locations. Similarly, both WRF-Chem and SPRINTARS simulated BC, which use emissions from EDGAR and a precompiled emission inventory, respectively, under predicted concentrations (P/O = 0.27 and P/O = 0.39) in this region [36]. WRF-Chem predicted CO with resolution of 30 km showed satisfactory model performance (P/O = 0.93) using HTAP-v2 emissions and over predictions (P/O = 1.33) using INTEX-B emissions [43]. Ozone was satisfactorily predicted by MOZART and WRF-Chem which used INTEX-B and RETRO emissions in two of three observation sites. Similarly, good model performance of predicted ozone was observed from WRF-CMAx simulations with in situ emissions at two sites (P/O = 1.14 and 0.94) [40]. However, in an another study, CMAQ predicted that ozone concentrations using in situ emissions showed satisfactory model (P/O = 0.9) performance at one location but over prediction at another (P/O = 1.52) [47].

Central India

Compared to other parts of the country, regional modeling studies in central India are rare. In one study, 20-km resolution WRF-Chem predicted that $PM_{2.5}$ concentrations with EDGAR emissions inventory showed under predictions at an urban location (P/O = 0.42) [34].

Summary of Regional Modeling Studies in India

MOZART and WRF-Chem were the most frequently used models in the studies across the country. Performance of studies using CMAQ (north P/O-1.21, west P/O-0.98, and south P/O-1.21) and WRF-Chem (north P/O-1.01, east P/O-0.805, west P/O-0.89, south P/O-0.63, and central P/O-0.42) were better. The performance of all models in semi-urban areas of north (P/O-1.06) and south (P/O-1.04) was better as compared to the studies in the corresponding urban areas. However, the performance of models in semi-urban and urban regions in east (P/O = 0.86) and west (P/O = 1.08) was comparable. HTAP-v2 (P/O-0.785) and EDGAR (P/O-0.74) emission inventory were commonly used models for predicting CO, O_3, and $PM_{2.5}$, respectively. Studies with in situ emission inventories performed satisfactorily (P/O-1.04), indicating the requirement of better representative finer scale emission inventories in India.

Local Scale

Local Statistical Models

Diverse Sources of PM over India

Figure 2 shows the source contributions to PM in different cities over India. PM concentrations in northern and eastern India were higher than cities in other parts of the country. These studies are further divided into residential, city center, and industrial areas in different regions of the country as described below.

Northern India

Around 19 RSA studies were carried out at Delhi in last decade with 37% in the last 5 years. RSA studies in other cities were fewer in number.

Delhi

Delhi, the capital city of India, often features in the world's top polluted cities list. Around 30% of its population was diagnosed with respiratory disorders caused due to air pollution [49] which led to 18,600 premature deaths every year [50].

Residential Area

In Delhi, most commonly found sources were traffic (23%), industrial emissions (29%), biomass burning (15.02%), and dust emissions (35%) [28, 29, 31, 32].

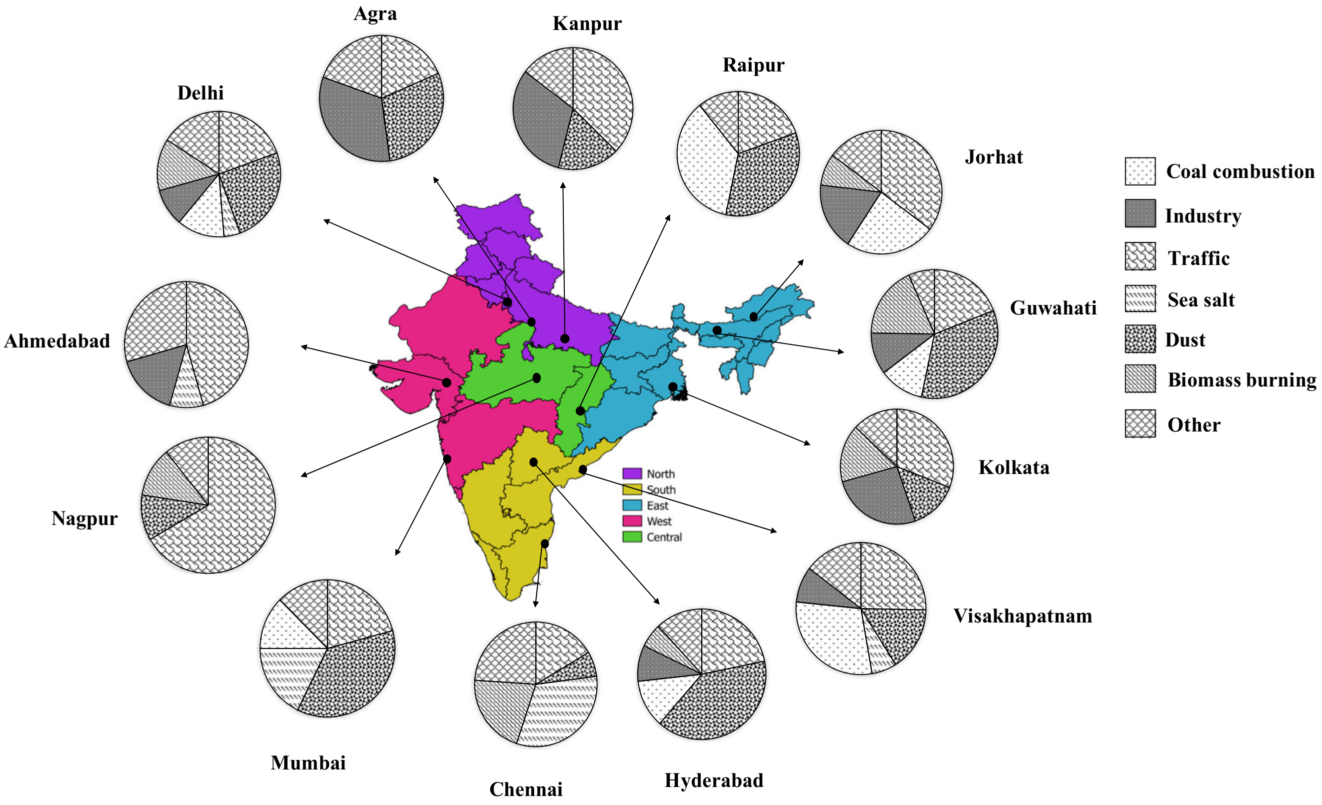

Fig. 2 Relative source contributions (%) of PM in major cities in India

City center

Traffic (20.3%), biomass burning (13.95%), industrial emissions (10.04%), dust (25.89%), coal combustion (12.94%), and sea salt (4.4%) were the major sources near city centers in Delhi [28, 29, 33–35].

Industrial Area

Most important sources were industrial emissions (46.2%), dust sources (22.8%), and traffic-related emissions (10.2%) [28].

Agra

Residential Area RSA studies conducted in residential areas of Agra [51, 52], one of the most polluted cities in Uttar Pradesh, identified traffic emissions (28%) and dust emissions (48%) as the major sources contributing to PM_{10}. While to $PM_{2.5}$, industrial emissions (30%), traffic emissions (17%), dust (27%), and other anthropogenic activities (18%) were the main sources. Dominant sources to water soluble ions in TSP were biomass burning and local soil [53]. Apportionment of PM sizes and trace metals in this region found the following sources [52]: traffic emission and soil dust (38.1%), fossil fuel combustion (25.8%), garbage burning, and other activities (25.7%).

City Center RSA study of PM_{10} identified that traffic (27.45%), biomass burning (13.67%), industrial emissions (13.52%), and dust emissions (30%) as the dominant sources contributing to PM_{10} [36, 37]. Concentrations of PM sizes and trace metals identified the following sources [52]: traffic emission and soil dust (47.6%), vehicular wear and tear (33.8%), and biomass burning (17.9%).

Kanpur Kanpur, which is located in central IGP region, poses constant threat of varying emission sources thereby leading to higher concentrations of PM. One of the studies conducted in a residential area [54] in this region found out traffic emissions (38.78%), industries (32.52%), and dust (17.07%) as major sources of PM_1. Another study in the same location found that anthropogenic sources were crucial during winter, while crustal emissions are high in summer [55].

Eastern India

Kolkata

Population in Kolkata, one of the megacities in India, is suffering from 41.3 to 47.8% of upper and lower respiratory issues, respectively [56]. Number of RSA studies carried out in Kolkata are 57% lesser than Delhi.

City Center

In order to identify sources of total suspended PM, road side locations in Kolkata were studied and found that traffic emissions (42%), dust (17%), and industrial emissions (7%) were the major sources [57]. Extensive sampling conducted in this megacity to understand the sources of $PM_{2.5}$ using PCA identified traffic emissions (38%), biomass burning (27%), dust (18%), and other secondary anthropogenic (11%) as the dominant sources [58].

Residential and Industrial

One of the studies conducted in 16 different locations of Kolkata (i.e., residential areas close to traffic junctions, coal fired power plants, industrial belts, waste incineration plants, cement factories, and brick kilns) identified major sources as traffic, industries, and coal combustion using PCA [59].

RSA studies in northeast India were mainly concentrated in the mid Brahmaputra valley region. One of the studies in suburban area, using enrichment factor (EF) found out that traffic induced emissions (38%), coal combustion (26%), industrial emissions (19%), and biomass burning (9%) were the dominant sources [60].

A study at a residential region [61], using PCA-multiple linear regression (MLR), marked three major sources: biomass burning (23%), dust (26%), and traffic emissions (22%).

Western India

Mumbai

Mumbai, the industrial capital of India, which is growing in all the commercial activities leading to the deterioration of air quality day-by-day. To understand these increasing sources, several RSA studies have been conducted in the past which are well discussed in the following section.

Residential Area

Sources to PM_{10} were dust (35%), sea salt (17%), coal combustion (12%), and traffic emissions (20%) and for $PM_{2.5}$ were dust (26%), industrial emissions (4%), sea salt (14%), and coal combustion (7%) [62].

City Center

In this city, major sources observed were dust emissions (11%) and sea salt (11%) for $PM_{2.5}$, and for PM_{10}, traffic emissions (22%), biomass burning (18%), sea salt (19%), and dust emissions (25%) [62].

Industrial Area

In this region, dominant sources found were dust emissions (10%) and sea salt (8%) for $PM_{2.5}$, and for PM_{10}, traffic emissions (25%), biomass burning (15%), and dust emissions (27%) [62].

Ahmedabad

Ahmedabad, a semi-arid and well-populated area in western India, has all types of settings like residential, small- and large-scale industries, commercial activities etc. Identification of the major sources to TSP using PMF revealed that dust (57%), biomass burning (10%), vehicular emissions (17%), and sea salt (5%) are the resolved factors [63]. Study using PMF, in a city center, reported the dominant sources of PM_{10} as dust (37%) and biomass burning (33%), and industrial emissions (11%), sea salt (6%), and vehicular emissions (31%) for $PM_{2.5}$ [64].

Nagpur

Nagpur, the centrally located fast growing metropolis city of India, is also victimized of poor air quality. A recent RSA study in which $PM_{2.5}$ sampling was carried out in Nagpur using CMB found the following major sources: vehicular emissions (57, 62, and 65%), biomass burning (15, 11, and 9%), and dust emissions (6, 10, and 7%) in residential, commercial, and industrial regions, respectively [65].

Southern India

RSA studies over South India have immensely increased during the last decade and is extensively concentrated in Chennai, Hyderabad, and Visakhapatnam.

Chennai

Sources to PM in a city center was studied and identified as dust emissions (74%), sea salt (16%), and traffic emissions (10%) [66]. Another study conducted in an urban site using PMF reported that sea salt (40.4% in PM_{10} and 21.5% in $PM_{2.5}$), traffic emissions (20% in PM_{10} and 11% in $PM_{2.5}$), biomass burning (0.7% in PM_{10} and 14% in $PM_{2.5}$), and dust emissions (3.4% in PM_{10} and 4.3% in $PM_{2.5}$) are the major sources [67].

Hyderabad

Hyderabad, an emerging metropolitan 400-year-old city, has an increasing trend of urbanization since 1960 due to which a significant degree of air quality decline is being witnessed. RSA in the city center identified dust emissions (40%), traffic emissions (22%), coal combustion (12%), industrial emissions (9%), and biomass burning (7%) as dominant sources for PM_{10} and traffic emissions (31%), dust (26%), coal combustion (9%), industrial emissions (7%), and biomass burning (6%) as the source contributors to $PM_{2.5}$ [68]. In a residential area, the common sources found were dust emissions (36 and 20%), traffic emissions (41 and 38%), biomass burning (6 and 9%), and coal combustion (6 and 12%) for both PM_{10} and $PM_{2.5}$, respectively.

Visakhapatnam

Visakhapatnam, also known as the financial capital of state of Andhra Pradesh, had gradual decline of air quality and thereby turning out to be air pollution hotspot. RSA of PM_{10} showed dust emissions (22.5%), sea salt (9.7%), coal combustion (15.5%), industrial emissions (5.1%), and biomass burning (35%) in residential sites, and dust emissions (22.5%), sea salt (5.5%), coal combustion (26.1%), industrial emissions (7.8%), and traffic (14%) in industrial sites [69].

Central India

Durg

RSA studies in other cities of the Central India are few. At a city center of Durg in Chhattisgarh, source identification study [70] using PCA revealed two principal components which explain 76.6 and 65.9% of the variance for $PM_{2.5}$ and PM_1, respectively. One component had coal combustion, traffic emissions, and biomass burning (52 and 45%) and another was dust emissions (25 and 21%).

Raipur

Study near city center, using PCA [71], revealed that while coal burning (33.2%), dust (31.6%), and traffic emissions (18.4%) were prominent sources contributing to $PM_{2.5}$, coal burning (50.7%), dust (25.3%), and traffic emissions (18%) were sources to PM_{10}.

Summary of Sources in Different Regions of India

In residential areas in north, south, east, and west, the dust emissions (42%), traffic (41%), traffic (30%), and dust emissions (43%) were the dominant sources. While in city centers in north, south, east, west, and central India, dust emissions (28%), dust emissions (47%), traffic (40%), traffic (42%), and coal combustion (45%) were the main sources. In industrial regions in north, south, and west, industrial emissions (46%), coal combustion (26%), and traffic emissions (44%) were important sources, respectively. Overall, in India, dust (30%) and traffic emissions (31%) are the main contributors to PM.

Diverse Sources of Components of Polycyclic Aromatic Hydrocarbons over India

In the recent years, studies on RSA of PAHs are gradually increasing every year with majority of them in cities. Sources of PAHs in Kolkata, identified using suitable biomarkers, were coal combustion, vehicle exhaust, and wood burning [72]. RSA study of PM_1 bound PAHs carried out using PCA reported that diesel vehicles and coal combustion were the predominant sources in Kanpur city [73]. In Delhi, a RSA study using PCA revealed that diesel, natural gas and lubricating oil combustion (49.5%), wood combustion (25.4%), gasoline (15.5%), and coal combustion (9.6%) as sources [74]. RSA results of PM_{10} bound PAHs found that vehicular exhaust, wood combustion, and coal combustion as most important sources in Mumbai city [75]. RSA of PAHs using PCA in Agra identified industries (44%), coal and wood combustion (22%), and gasoline driven vehicles (14%) as the major sources [76]. Another study of fine particulate phase PAHs in Chennai using PCA model identified that vehicular emissions, off-road combustion activities such as wood, solid waste, and other garbage as the dominant sources [77]. $PM_{2.5}$ bound PAHs in Tiruchirappalli identified the sources using PCA as diesel engine emissions (31.71%), vehicle emissions (28.2%), and gasoline emissions (14.5%) as dominant sources [78].

Diverse Sources of Components of Volatile Organic Compounds over India

VOCs are the group of species containing non-methane oxygenated and halogenated hydrocarbons released from anthropogenic and natural sources. Toxicity of VOCs is severe where it ranges from respiratory irritation to carcinogenic effects such as lung, blood, and kidney. However, in Indian context, the focus on VOCs is far less compared to the importance given to PM. A study in city center of Delhi revealed following major sources using CMB: diesel engine exhaust (26–58%), vehicle exhaust (14–23%), evaporative exhaust (10–18%), auto repair (4–16%), degreasing (2–4%), and natural gas (2–12%) [79]. A recent study using PCA in a residential area of Delhi found the dominant sources contributing to VOCs as traffic emissions (37%), solvent usage and degreasing solvents (19%), and industrial emissions (13%) [80]. Studies carried out in Mumbai in a city center, using factor analysis, found that evaporative emissions (60–70%), vehicle exhaust composite (11–33%), degreasing (2–20%), diesel internal combustion (4%), and refinery (21%) as the important sources [81, 82]. In Kolkata, SA study using CMB in a city center observed vehicle exhaust (38.8–44.8%), coal combustion (up to 37.9%), and other source (pesticides, wood combustion, printing) as major sources [83].

Studies in Raipur (in an industrial site), Ahmedabad (at a city center), and Dehradun (at a city center) concluded that apart from contributions from vehicular emissions, emissions from natural gas and leakage of liquefied petroleum gas (LPG) can be major [84–86].

Local Numerical Models

Northern India

Urban

Industrial Source Complex (ISCST3) models were used to predict PM_{10} concentrations at 2-km resolution in an industrial area using an in situ emission inventory [87]. The model under predicted concentrations at seven locations (P/O 0.45–0.61). In another study, AERMOD was used to determine the total suspended particulate matter in an urban area using in situ emission inventory at 2-km resolution [88]. The model was found to satisfactorily predict concentrations in Delhi (P/O = 0.86). In another study using AERMOD [89] with in situ emissions revealed that while NO_x and PM_{10} were predicted satisfactory (P/O = 1.22 and 0.85), SO_2 was under predicted (P/O = 0.68). While AERMOD satisfactorily predicted total suspended PM (TSPM) concentrations in Delhi (P/O = 0.84), atmospheric dispersion modeling system (ADMS) under predicted the concentrations (P/O = 0.77) [90]. SPM model with in situ emission inventory was used to determine the roles of various sources affecting TSPM concentrations [91]. While the predictions when compared with observations using emissions from only vehicles were lower (P/O = 0.78), predictions with vehicle and natural emissions (P/O = 0.86), vehicle and domestic emissions (P/O = 0.87) and vehicle, natural and domestic emissions (P/O = 0.92) were found to be closer to observations. California Line source (CALINE4) model was used to predict concentrations in flat and hilly locations [92] using in situ emission inventory calculated using vehicle emission factors from ARAI [93]. While the model slightly under predicted concentrations in flat terrain (P/O = 0.72), it severely over predicted concentrations in hilly terrain (P/O = 3.14). Similarly, impact of diesel vehicles on air quality was studied using CALINE and Indian Institute of Technology Line Source (IITLS) models with in situ emissions [94]. Both models under predict concentrations in Delhi, with IITLS (P/O = 0.61) having a slightly better performance as compared to CALINE (P/O = 0.51). In another study, IITLS and ISCST3 were used with an in situ emissions [95]. Results showed that while IITLS model slightly over predicted Pb (P/O = 1.28), ISCST3 under predicted (P/O = 0.63) the same.

Semi-Urban

An assessment of air quality in an industrial area using GFLSM and ISCST3 with in situ emissions revealed that industries were the main source followed by vehicles [96]. Both the models under predicted NO_2 concentrations (P/O = 0.23 and 0.73 using GFLSM and ISCST3, respectively).

Eastern India

Urban

Roadside air quality was evaluated at a busy traffic intersection using CALINE3, General Finite Line Source Model (GFLSM), and CAL3QHC [97] using vehicular emissions computed from emission factors provided by national environmental research institute [98]. Models were able to predict PM_{10} and $PM_{2.5}$ concentrations satisfactorily. P/O for GFLSM, CALINE3, and CAL3QHC were 0.78, 1.21, 0.93 for PM_{10} and 1, 1.13, and 1.39 for $PM_{2.5}$.

Semi-Urban

Similarly, assessment of contribution of SO_2 and NO_2 from different sources in an industrial area [99] using in situ emissions [100]. While NO_2 was under predicted (P/O = 0.41), SO_2 predictions were satisfactory (P/O = 0.98).

Western India

Urban

An unsteady and a steady-state dispersion model was used to understand the effect of meteorology on ambient concentrations using in situ emission inventory in an urban area [101]. While irrespective of mixing layer heights, the steady-state model had similar performance, the unsteady state model over predicted 24-h concentrations at 50-m mixing layer height (P/O = 1.5), and satisfactorily predicted concentrations at 100 m (P/O = 0.90). In an another study, NO_x and PM concentrations were modeled using Operational Street Pollution Model (OSPM) [102] with ARAI provided emission inputs [93]. The model prediction in Mumbai indicates under prediction of PM (P/O = 0.56) and slight over prediction of NO_x (P/O = 1.28). A study used chemical transport model to simulate PM_{10} concentration using in situ emission inventory at 1-km resolution [103]. The predictions were found to be satisfactory for Ahmedabad (P/O = 1.02) while Surat (P/O = 0.78) and Rajkot (P/O = 0.66) were found to be under predicted. Another similar study was carried out in an urban area using AERMOD to evaluate PM_{10} concentrations with WRF meteorological inputs [104]. Model under predicted concentrations at commercial (P/O = 0.63), background (P/O = 0.38), residential (P/O = 0.72), and sensitive (P/O = 0.31) regions.

Southern India

Urban

Effect of stone crushing units on PM concentration was evaluated in an urban area [105]. Three models FDM, ISCST3, and AERMOD were used for modeling dust emissions. Model results indicated dust concentrations to exceed INAAQS. Out of the three models, AERMOD was the better in predicting dust concentrations (P/O = 0.80) as compared to ISCST3 (P/O = 0.53) and FDM (P/O = 1.84). Furthermore, model simulation at other nearby areas was also carried out to determine the effect of quarry using AERMOD, ISCST3, and FDM: Saranagar (P/O = 0.54, 0.72, and 1.27), Zamin Pallavaram (P/O = 0.45, 1.02, and 1.12), Everedy nagar (P/O = 0.27, P/O = 6.09, and P/O = 0.16), Krushna nagar (P/O = 1.36, P/O = 5.37, and P/O = 0.19), and Kennady nagar (P/O = 0.52, P/O = 11.24, and P/O = 0.10). As observed, barring AERMOD, the other two models either severely over or under predicted concentrations. Another study used ATMOS to simulate PM_{10}, SO_2, and NO_2 concentrations [106]. The PM_{10} concentration was found to be satisfactory in two urban locations (P/O = 1.20 and 0.91). Similarly, another study using SIM-air quality modeling tools in Chennai predicted PM_{10} concentrations satisfactorily (P/O = 1.03) [103]. In another study, ISCST3 model was used to study the impact of industries on air quality [107]. The model performance for SO_2 at Hyderabad in the months of May and April indicated over predictions (P/O = 1.27 and 1.48, respectively).

Semi-Urban

AERMOD satisfactorily predicted PM_{10} concentrations at three semi-urban sites (P/O = 0.78–0.88) [108]. The study concluded that transportation, small-scale industries, and combustion of conventional fuels were the sources of particulate pollution. ISCST3 model performed satisfactorily (P/O = 0.89), while Gaussian Plume Model (GPM) under predicted (P/O = 0.67) NO_x and SO_2 [109].

Central India

SIM-air using ATMOS chemical transport model was used for predicting PM_{10} concentrations with in situ emission inventory at 1-km resolution in an urban area [110]. The simulated concentration of PM_{10} was found to be satisfactory (P/O = 0.82) when compared with observed values in Indore.

Summary of Local Numerical Modeling Studies in India

Similar to regional modeling studies, emissions resulted in huge uncertainties in local numerical models. ATMOS (west P/O-0.9, south P/O-1.03, and central India P/O-0.82) and AERMOD (north P/O-0.85, west P/O-0.50, and south P/O-0.78) models with improved treatment of emission inputs performed better compared to other models. AERMOD and ISCST3 were the most frequently used models.

Conclusion

Till date, no critical review which combined both local and regional air quality modeling studies, which is extremely essential for the proper formulation of air quality abatement strategies, was carried out in India. A total of 130 publications available in citation databases were intently reviewed and the principal findings are well comprised below:

(i) Very few local and regional studies are carried out in central India. Moreover, owing to higher concentrations in Indo Gangetic plain, more studies are concentrated in northern India. For example, 74% RSA studies are documented from Northern and eastern India.

(ii) Most of the PM studies in the country are either on $PM_{2.5}$ or PM_{10}; thus, more studies are required to identify sources and contributions of size resolved PM.

(iii) RSA studies on PM are numerous when compared to VOCs and PAHs which are highly carcinogenic and need greater attention.

(iv) Inconsistent selection of the source tracers holds the point of ambiguity in RSA studies.

(v) Heterogeneous sources at different regions of India lead to varied spatio-temporal, physical, and chemical characteristics of PM. In northern region, while dust emissions are dominant source in Delhi, industry followed by traffic emissions are major sources in Kanpur and Agra. Traffic and dust emissions are commonly reported dominant sources followed by coal combustion in southern and eastern cities of India. Almost all the cities in coastal regions have profound sea salt contributions.

(vi) Performance of regional models with finer resolution was better than coarser models.

(vii) Irrespective of the emission inventory and the model used, most of the regional studies under predict PM concentrations in Delhi. While the same model set up is doing decent job elsewhere. This could be due to missing out a dominant source in the region. One way to approach the problem could be by modifying the existing emission inventories based on results from the local RSA studies.

(viii) The problem of lack of reliable emission inventory is also evident from the analysis of local numerical models. For example, unavailability of load dependent emission factors for vehicles led to either under or over prediction of target pollutants in most of the studies.

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Compliance with ethical standards

Conflict of Interest The authors have no affiliations with any organization or entity with any interest in the materials discussed in this manuscript.

References

1. WHO. WHO Global Urban Ambient Air Pollution Database (update 2016) 2016 [cited 2017 11th,Feb]. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/.
2. CPCB. National Ambient Air Quality Status 2008 [cited 2017 12th April]. Available from: http://cpcb.nic.in/upload/NewItems/NewItem_147_report-2008.pdf.
3. CPCB. Central Pollution Control Board 2015 [cited 2018 24th, Jan]. Available from: http://www.cpcb.gov.in/CAAQM/frmUserAvgReportCriteria.aspx.
4. CPCB. Central pollution control board. Annual Report. New-Delhi: India; 2016.
5. IHME. State of global air, A special report on global exposure to air pollution and its disease burden. Institute for Health Metrics and Evaluation, 2017.
6. Sahu SK, Kota SH. Significance of PM2. 5 air quality at the Indian capital. Aerosol Air Qual Res. 2017;17(2):588–97.
7. Wang Y, Ying Q, Hu J, Zhang H. Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013–2014. Environ Int. 2014;73:413–22.
8. Han F, Kota SH, Wang Y, Zhang H. Source apportionment of PM2.5 in baton rouge, Louisiana during 2009–2014. Sci Total Environ. 2017;586:115–26.
9. Gupta P, Christopher SA, Wang J, Gehrig R, Lee Y, Kumar N. Satellite remote sensing of particulate matter and air quality assessment over global cities. Atmos Environ. 2006;40(30):5880–92.
10. Kharol SK, Badarinath K, Sharma AR, Mahalakshmi D, Singh D, Prasad VK. Black carbon aerosol variations over Patiala city, Punjab, India—a study during agriculture crop residue burning period using ground measurements and satellite data. J Atmos Sol Terr Phys. 2012;84:45–51.
11. Kota SH, Ying Q, Zhang Y. Simulating near-road reactive dispersion of gaseous air pollutants using a three-dimensional Eulerian model. Sci Total Environ. 2013;454:348–57.
12. Kota SH, Zhang H, Chen G, Schade GW, Ying Q. Evaluation of on-road vehicle CO and NOx National Emission Inventories using an urban-scale source-oriented air quality model. Atmos Environ. 2014;85:99–108.
13. Ying Q, Li J, Kota SH. Significant contributions of isoprene to summertime secondary organic aerosol in eastern United States. Environ Sci Technol. 2015;49(13):7834–42.
14. Markakis K, Valari M, Perrussel O, Sanchez O, Honore C. Climate-forced air-quality modeling at the urban scale: sensitivity to model resolution, emissions and meteorology. Atmos Chem Phys. 2015;15(13):7703–23.
15. Sillman S, Logan JA, Wofsy SC. The sensitivity of ozone to nitrogen oxides and hydrocarbons in regional ozone episodes. J Geophys Res: Atmospheres. 1990;95(D2):1837–51.
16. Kota SH, Ying Q, Zhang Y. TAMNROM-3D: three-dimensional Eulerian model to simulate air quality near highways. Transp Res Rec: J Transp Res Board. 2010;2158:61–8.
17. Kota SH, Park C, Hale MC, Werner ND, Schade GW, Ying Q. Estimation of VOC emission factors from flux measurements using a receptor model and footprint analysis. Atmos Environ. 2014;82:24–35.
18. Hu J, Chen J, Ying Q, Zhang H. One-year simulation of ozone and particulate matter in China using WRF/CMAQ modeling system. Atmos Chem Phys. 2016;16(16):10333–50.
19. Kota SH, Schade G, Estes M, Boyer D, Ying Q. Evaluation of MEGAN predicted biogenic isoprene emissions at urban locations in Southeast Texas. Atmos Environ. 2015;110:54–64.
20. Shi Z, Li J, Huang L, Wang P, Wu L, Ying Q, et al. Source apportionment of fine particulate matter in China in 2013 using a source-oriented chemical transport model. Sci Total Environ. 2017;601-602:1476–87.
21. Guo H, Kota SH, Sahu SK, Hu J, Ying Q, Gao A, et al. Source apportionment of PM2.5 in North India using source-oriented air quality models. Environ Pollut. 2017;231(Part 1):426–36.
22. Thunis P, Miranda A, Baldasano JM, Blond N, Douros J, Graff A, et al. Overview of current regional and local scale air quality modelling practices: assessment and planning tools in the EU. Environ Sci Pol. 2016;65:13–21.
23. Sharma S, Sharma P, Khare M. Photo-chemical transport modelling of tropospheric ozone: a review. Atmos Environ. 2017;159:34–54.
24. Zhang Y, Cai J, Wang S, He K, Zheng M. Review of receptor-based source apportionment research of fine particulate matter and its challenges in China. Sci Total Environ. 2017;
25. Belis C, Karagulian F, Larsen B, Hopke P. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. Atmos Environ. 2013;69:94–108.
26. Banerjee T, Murari V, Kumar M, Raju M. Source apportionment of airborne particulates through receptor modeling: Indian scenario. Atmos Res. 2015;164:167–87.
27. Singh N, Murari V, Kumar M, Barman SC, Banerjee T. Fine particulates over South Asia: review and meta-analysis of PM2.5 source apportionment through receptor model. Environ Pollut. 2017;223:121–36.
28. Moorthy KK, Beegum SN, Srivastava N, Satheesh SK, Chin M, Blond N, et al. Performance evaluation of chemistry transport models over India. Atmos Environ. 2013;71:210–25.
29. Chang JC, Hanna SR. Air quality model performance evaluation. Meteorog Atmos Phys. 2004;87(1):167–96.
30. Banerjee T, Murari V, Kumar M, Raju MP. Source apportionment of airborne particulates through receptor modeling: Indian scenario. Atmos Res. 2015;164:167–87.
31. Pant P, Guttikunda SK, Peltier RE. Exposure to particulate matter in India: a synthesis of findings and future directions. Environ Res. 2016;147:480–96.
32. Karagulian F, Belis CA, Dora CFC, Prüss-Ustün AM, Bonjour S, Adair-Rohani H, et al. Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. Atmos Environ. 2015;120:475–83.
33. Gupta M, Mohan M. Assessment of contribution to PM10 concentrations from long range transport of pollutants using WRF/Chem over a subtropical urban airshed. Atmos Pollut Res. 2013;4(4):405–10.
34. Bran SH, Srivastava R. Investigation of PM2.5 mass concentration over India using a regional climate model. Environ Pollut. 2017;224:484–93.

35. Diehl T, Heil A, Chin M, Pan X, Streets D, Schultz M, et al. Anthropogenic, biomass burning, and volcanic emissions of black carbon, organic carbon, and SO2 from 1980 to 2010 for hindcast model experiments. Atmos Chem Phys Discuss. 2012;2012:24895–954.
36. Govardhan GR, Nanjundiah RS, Satheesh SK, Moorthy KK, Takemura T. Inter-comparison and performance evaluation of chemistry transport models over Indian region. Atmos Environ. 2016;125(Part B):486–504.
37. Srivastava R, Bran SH. Spatio-temporal variations of black carbon and optical properties in a regional climate model. Int J Climatol. 2017;37(3):1432–43.
38. Sheel V, Lal S, Richter A, Burrows JP. Comparison of satellite observed tropospheric NO2 over India with model simulations. Atmos Environ. 2010;44(27):3314–21.
39. Gupta M, Mohan M. Validation of WRF/Chem model and sensitivity of chemical mechanisms to ozone simulation over megacity Delhi. Atmos Environ. 2015;122:220–9.
40. Sarkar M, Venkataraman C, Guttikunda S, Sadavarte P. Indian emissions of technology-linked NMVOCs with chemical speciation: an evaluation of the SAPRC99 mechanism with WRF-CAMx simulations. Atmos Environ. 2016;134:70–83.
41. Sharma S, Chatani S, Mahtta R, Goel A, Kumar A. Sensitivity analysis of ground level ozone in India using WRF-CMAQ models. Atmos Environ. 2016;131:29–40.
42. Kumar R, Naja M, Pfister G, Barth M, Wiedinmyer C, Brasseur G. Simulations over South Asia using the weather research and forecasting model with chemistry (WRF-Chem): chemistry evaluation and initial results. Geosci Model Dev. 2012;5(3):619–48.
43. Ojha N, Pozzer A, Rauthe-Schöch A, Baker AK, Yoon J, Brenninkmeijer CAM, et al. Ozone and carbon monoxide over India during the summer monsoon: regional emissions and transport. Atmos Chem Phys. 2016;16(5):3013–32.
44. Gogoi MM, Babu SS, Moorthy KK, Bhuyan PK, Pathak B, Subba T, et al. Radiative effects of absorbing aerosols over northeastern India: observations and model simulations. J Geophys Res: Atmospheres. 2017;122(2):1132–57.
45. Surendran DE, Ghude SD, Beig G, Emmons LK, Jena C, Kumar R, et al. Air quality simulation over South Asia using hemispheric transport of air pollution version-2 (HTAP-v2) emission inventory and model for ozone and related chemical tracers (MOZART-4). Atmos Environ. 2015;122:357–72.
46. Jena C, Ghude SD, Pfister GG, Chate DM, Kumar R, Beig G, et al. Influence of springtime biomass burning in South Asia on regional ozone (O3): a model based case study. Atmos Environ. 2015;100:37–47.
47. Chatani S, Amann M, Goel A, Hao J, Klimont Z, Kumar A, et al. Photochemical roles of rapid economic growth and potential abatement strategies on tropospheric ozone over south and East Asia in 2030. Atmos Chem Phys. 2014;14(17):9259–77.
48. Beig G, Gunthe S, Jadhav DB. Simultaneous measurements of ozone and its precursors on a diurnal scale at a semi urban site in India. J Atmos Chem. 2007;57(3):239–53.
49. Kandlikar M, Ramachandran G. The causes and consequences of particulate air pollution in urban india: a synthesis of the science. Annu Rev Energy Environ. 2000;25(1):629–84.
50. TERI. (The Energy and Resources Institute) State of Environment Report for Delhi 2001 Report No. 2000EE65 Supported by the Department of Environment, Government of National Capital Territory, Delhi, TERI, New Delhi (2001).
51. Kulshrestha A, Satsangi PG, Masih J, Taneja A. Metal concentration of PM2.5 and PM10 particles and seasonal variations in urban and rural environment of Agra, India. Sci Total Environ. 2009;407(24):6196–204.
52. Habil M, Massey DD, Taneja A. Exposure of children studying in schools of India to PM levels and metal contamination: sources and their identification. Air Qual Atmos Health. 2013;6(3):575–87.
53. Satsangi A, Pachauri T, Singla V, Lakhani A, Kumari KM. Water soluble ionic species in atmospheric aerosols: concentrations and sources at Agra in the indo-Gangetic plain (IGP). Aerosol Air Qual Res. 2013;13:1877–89.
54. Chakraborty A, Gupta T. Chemical characterization of submicron aerosol in Kanpur region: a source apportionment study. Int J Env Ac Eng. 2009;1:19–27.
55. Ram K, Sarin MM, Tripathi SN. Temporal trends in atmospheric PM2.5, PM10, elemental carbon, organic carbon, water-soluble organic carbon, and optical properties: impact of biomass burning emissions in the indo-Gangetic plain. Environ Sci Technol. 2012;46(2):686–95.
56. WBPCB. A Report on Trend of Important Air Quality Parameters in Kolkata during Night Time as Compared to Daytime Situation during Year 2011 and 2012. 2012:61.
57. Kar S, Maity JP, Samal AC, Santra SC. Metallic components of traffic-induced urban aerosol, their spatial variation, and source apportionment. Environ Monit Assess. 2010;168(1):561–74.
58. Chatterjee A, Dutta C, Jana TK, Sen S. Fine mode aerosol chemistry over a tropical urban atmosphere: characterization of ionic and carbonaceous species. J Atmos Chem. 2012;69(2):83–100.
59. Das R, Khezri B, Srivastava B, Datta S, Sikdar PK, Webster RD, et al. Trace element composition of PM 2.5 and PM 10 from Kolkata–a heavily polluted Indian metropolis. Atmos Pollut Res. 2015;6(5):742–50.
60. Khare P, Baruah BP. Elemental characterization and source identification of PM 2.5 using multivariate analysis at the suburban site of north-east India. Atmos Res. 2010;98(1):148–62.
61. Deka P, Bhuyan P, Daimari R, Sarma KP, Hoque RR. Metallic species in PM10 and source apportionment using PCA-MLR modeling over mid-Brahmaputra Valley. Arab J Geosci. 2016;9(5):335.
62. Kothai P, Saradhi I, Pandit G, Markwitz A, Puranik V. Chemical characterization and source identification of particulate matter at an urban site of Navi Mumbai. India Aerosol and Air Quality Resarch. 2011;11(5):560–9.
63. Raman RS, Ramachandran S, Rastogi N. Source identification of ambient aerosols over an urban region in western India. J Environ Monit. 2010;12(6):1330–40.
64. Sudheer A, Rengarajan R. Atmospheric mineral dust and trace metals over urban environment in western India during winter. Aerosol Air Qual Res. 2012;12(5):923–33.
65. Pipalatkar P, Khaparde VV, Gajghate DG, Bawase MA. Source apportionment of PM2. 5 using a CMB model for a centrally located Indian city. Aerosol Air Qual Res. 2014;14:1089–99.
66. Srimuruganandam B, Nagendra SS. Characteristics of particulate matter and heterogeneous traffic in the urban area of India. Atmos Environ. 2011;45(18):3091–102.
67. Srimuruganandam B, Shiva Nagendra SM. Application of positive matrix factorization in characterization of PM10 and PM2.5 emission sources at urban roadside. Chemosphere. 2012;88(1):120–30.
68. Gummeneni S, Yusup YB, Chavali M, Samadi S. Source apportionment of particulate matter in the ambient air of Hyderabad city, India. Atmos Res. 2011;101(3):752–64.
69. Police S, Sahu SK, Pandit GG. Chemical characterization of atmospheric particulate matter and their source apportionment at an emerging industrial coastal city, Visakhapatnam, India. Atmos Pollut Res. 2016;7(4):725–33.
70. Deshmukh DK, Deb MK, Tsai YI, Mkoma SL. Water soluble ions in PM2. 5 and PM1 aerosols in Durg city, Chhattisgarh, India. Aerosol Air Qual Res. 2011;11:696–708.
71. Deshmukh DK, Deb MK, Suzuki Y, Kouvarakis GN. Water-soluble ionic composition of PM2.5–10 and PM2.5 aerosols in

the lower troposphere of an industrial city Raipur, the eastern central India. Air Qual Atmos Health. 2013;6(1):95–110.
72. Saha M, Maharana D, Kurumisawa R, Takada H, Yeo BG, Rodrigues AC, et al. Seasonal trends of atmospheric PAHs in five Asian megacities and source detection using suitable biomarkers. Aerosol Air Qual Res. 2017;17(9):2247–62.
73. Singh DK, Gupta T. Effect through inhalation on human health of PM1 bound polycyclic aromatic hydrocarbons collected from foggy days in northern part of India. J Hazard Mater. 2016;306:257–68.
74. Jyethi DS, Khillare PS, Sarkar S. Particulate phase polycyclic aromatic hydrocarbons in the ambient atmosphere of a protected and ecologically sensitive area in a tropical megacity. Urban For Urban Green. 2014;13(4):854–60.
75. Herlekar M, Joseph AE, Kumar R, Gupta I. Chemical speciation and source assignment of particulate (PM10) phase molecular markers in Mumbai. Aerosol Air Qual Res. 2012;12(6):1247–60.
76. Lakhani A. Source apportionment of particle bound polycyclic aromatic hydrocarbons at an industrial location in Agra, India. Sci World J. 2012;2012:10.
77. Mohanraj R, Solaraj G, Dhanakumar S. Fine particulate phase PAHs in ambient atmosphere of Chennai metropolitan city, India. Environ Sci Pollut Res. 2011;18(5):764–71.
78. Mohanraj R, Solaraj G, Dhanakumar S. PM 2.5 and PAH concentrations in urban atmosphere of Tiruchirappalli, India. Bull Environ Contam Toxicol. 2011;87(3):330–5.
79. Srivastava A, Sengupta B, Dutta SA. Source apportionment of ambient VOCs in Delhi City. Sci Total Environ. 2005;343(1–3):207–20.
80. Kumar A, Singh D, Anandam K, Kumar K, Jain VK. Dynamic interaction of trace gases (VOCs, ozone, and NOx) in the rural atmosphere of sub-tropical India. Air Qual Atmos Health. 2017;10(7):885–96.
81. Srivastava K, P, Pandit G, Sharma S, Mohan Rao M, A. Volatile organic compounds in indoor environments in Mumbai. India; 2000. p. 161–8.
82. Srivastava A, Joseph AE, Nair S. Ambient levels of benzene in Mumbai city. Int J Environ Health Res. 2004;14(3):215–22.
83. Majumdar D, Dutta C, Mukherjee AK, Sen S. Source apportionment of VOCs at the petrol pumps in Kolkata, India; exposure of workers and assessment of associated health risk. Transp Res Part D: Transp Environ. 2008;13(8):524–30.
84. Bauri N, Bauri P, Kumar K, Jain VK. Evaluation of seasonal variations in abundance of BTXE hydrocarbons and their ozone forming potential in ambient urban atmosphere of Dehradun (India). Air Qual Atmos Health. 2016;9(1):95–106.
85. Sharma S, Giri B, Patel KS. Ambient volatile organic compounds in the atmosphere of industrial central India. J Atmos Chem. 2016;73(4):381–95.
86. Sahu LK, Lal S. Distributions of C2–C5 NMHCs and related trace gases at a tropical urban site in India. Atmos Environ. 2006;40(5):880–91.
87. Behera SN, Sharma M, Dikshit O, Shukla SP. GIS-based emission inventory, dispersion modeling, and assessment for source contributions of particulate matter in an urban environment. Water Air Soil Pollut. 2011;218(1):423–36.
88. Mohan M, Bhati S, Rao A. Application of air dispersion modelling for exposure assessment from particulate matter pollution in mega city Delhi. Asia Pac J Chem Eng. 2011;6(1):85–94.
89. Gulia S, Shrivastava A, Nema A, Khare M. Assessment of urban air quality around a heritage site using AERMOD: a case study of Amritsar City, India. Environ Model Assess. 2015;20(6):599–608.
90. Mohan M, Bhati S, Sreenivas A, Marrapu P. Performance evaluation of AERMOD and ADMS-urban for total suspended particulate matter concentrations in megacity Delhi. Aerosol Air Qual Res. 2011;11(7):883–94.
91. Goswami P, Baruah J. Simulation of daily variation of suspended particulate matter over Delhi: relative roles of vehicular emission, dust, and domestic appliances. Mon Weather Rev. 2008;136(9):3597–607.
92. Dhyani R, Singh A, Sharma N, Performance GS. Evaluation of CALINE 4 model in a hilly terrain–a case study of highway corridors in Himachal Pradesh (India). Int J Environ Pollut. 2013;52(3–4):244–62.
93. india Tarao. Emission Factor development for Indian Vehicles. Pune: ARAI, Pune, 2008.
94. Goyal P, Jaiswal N, Kumar A, Dadoo JK, Dwarakanath M. Air quality impact assessment of NOx and PM due to diesel vehicles in Delhi. Transp Res Part D: Transp Environ. 2010;15(5):298–303.
95. Goyal P, Singh M, Bandopadhyay T, Krishna TR. Comparative study of line source models for estimating lead levels due to vehicular traffic in Delhi. Environ Softw. 1995;10(4):289–99.
96. Banerjee T, Barman S, Srivastava R. Application of air pollution dispersion modeling for source-contribution assessment and model performance evaluation at integrated industrial estate-Pantnagar. Environ Pollut. 2011;159(4):865–75.
97. Gokhale S, Raokhande N. Performance evaluation of air quality models for predicting PM10 and PM2.5 concentrations at urban traffic intersection during winter period. Sci Total Environ. 2008;394(1):9–24.
98. NEERI. National Environmental Engineering Research Institute, A report on air quality control. 2000.
99. Bhanarkar A, Goyal S, Sivacoumar R, Rao CC. Assessment of contribution of SO 2 and NO 2 from different sources in Jamshedpur region, India. Atmos Environ. 2005;39(40):7745–60.
100. TERI. Environmental effects of energy production. Transformation and Consumptionin NCR. New Delhi: India; 1992.
101. Venkatram A, Cimorelli AJ. On the role of nighttime meteorology in modeling dispersion of near surface emissions in urban areas. Atmos Environ. 2007;41(4):692–704.
102. Kumar A, Ketzel M, Patil RS, Dikshit AK, Hertel O. Vehicular pollution modeling using the operational street pollution model (OSPM) for Chembur, Mumbai (India). Environ Monit Assess. 2016;188(6):349.
103. Guttikunda SK, Jawahar P. Application of SIM-air modeling tools to assess air quality in Indian cities. Atmos Environ. 2012;62:551–61.
104. Kesarkar AP, Dalvi M, Kaginalkar A, Ojha A. Coupling of the weather research and forecasting model with AERMOD for pollutant dispersion modeling. A case study for PM10 dispersion over Pune, India. Atmos Environ. 2007;41(9):1976–88.
105. Sivacoumar R, Mohan Raj S, Chinnadurai SJ, Jayabalou R. Modeling of fugitive dust emission and control measures in stone crushing industry. J Environ Monit. 2009;11(5):987–97.
106. Guttikunda SK, Goel R, Mohan D, Tiwari G, Gadepalli R. Particulate and gaseous emissions in two coastal cities—Chennai and Vishakhapatnam, India. Air Qual Atmos Health. 2015;8(6):559–72.
107. Krishna TR, Reddy M, Reddy R, Singh R. Impact of an industrial complex on the ambient air quality: case study using a dispersion model. Atmos Environ. 2005;39(29):5395–407.
108. Bhaskar BV, Rajasekhar RJ, Muthusubramanian P, Kesarkar AP. Measurement and modeling of respirable particulate (PM10) and lead pollution over Madurai, India. Air Qual Atmos Health. 2008;1(1):45–55.
109. Krishna TR, Reddy M, Reddy R, Singh R. Assimilative capacity and dispersion of pollutants due to industrial sources in Visakhapatnam bowl area. Atmos Environ. 2004;38(39):6775–87.
110. Guttikunda SK, Jawahar P. Application of SIM-air modeling tools to assess air quality in Indian cities. Atmos Environ. 2012;62(Supplement C):551–61.