Source apportionment, health effects and potential reduction of fine particulate matter (PM$_{2.5}$) in India

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Executive summary

In recent years, severe pollution events occurred frequently in India, which are of significant concern of the public. However, limited studies have been conducted to understand the formation, sources and health effects of high pollution and the information for design of effective control strategies is urgently needed. In this work, source-oriented versions of the Community Multi-scale Air Quality (CMAQ) model with anthropogenic emissions from Emissions Database for Global Atmospheric Research (EDGAR), biogenic emissions from the Model for Emissions of Gases and Aerosols from Nature (MEGAN) v2.1, and meteorology from the Weather Research and Forecasting (WRF) model 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 major components including primary PM (PPM) and secondary inorganic aerosol (SIA) in India in 2015. Then, the health risks were estimated based on the predicted $PM_{2.5}$ concentrations and the air quality benefits from potential policy interventions in future were analyzed.

Concentrations of $PM_{2.5}$ were highest in the Indo-Gangetic region, including northern and eastern India. $PM_{2.5}$ concentrations were higher during winter and lower during monsoon season. Winter nitrate concentrations were 160-230% higher than yearly average. In contrast, the fraction of sulfate in total $PM_{2.5}$ was maximum in monsoon and least in winter, due to decrease in temperature and solar radiation intensity in winter. Except in southern India, where sulfate was the major component of $PM_{2.5}$, primary organic aerosol (POA) fraction in $PM_{2.5}$ was highest in all regions of the country. Fractions of secondary components were higher on bad days than on good days, indicating the importance of control of precursors for secondary pollutants in India.

PPM 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 $PM_{2.5}$.

The major source of PPM mass is from within the state. In the selected cities, Chandigarh is the capital of the northern Indian states of Punjab and Haryana, Jaipur is the capital of India's Rajasthan state, and Lucknow is the capital of the state of Uttar Pradesh and Delhi. About 80% of PPMs are from within the state in these 4 cities. Similar to PPM analysis, 80% of the total ammonia PM concentrations are from within the state, but Delhi have 20% of the total ammonia PMs from the adjacent states: Haryana, Rajasthan, Uttar Pradesh and Uttarakhand. In contrast, the nitrate PM in Delhi comes mainly from 3 sources: within the state, Haryana & Rajasthan and Punjab, Himachal Pradesh and Jammu&Kashmir. Each region contributes ~25% to total nitrate PM in Delhi. In other 3 cities, sources within the state contribution dominates total nitrate PM concentrations. The sulfate is formed mainly through rapid oxidation in emission plumes (40%~70% in Delhi). However, the secondary sulfate PMs are more likely from sources within the state in Lucknow and Jaipur.

Premature mortality associated with $PM_{2.5}$ exposure was mainly due to cerebrovascular disease (CEV) was the highest in India (0.44 million), followed by ischaemic heart disease (IHD, 0.40 million), chronic obstructive pulmonary disease (COPD, 0.18 million) and lung cancer (LC, 0.01 million), adding up to total morality of 1.04 million. The top states of premature mortality were Uttar Pradesh (0.23 million), Bihar (0.12 million) and West Bengal (0.10 million). The residential sector was the top contributor (55.45%) to total premature mortality with a concentration of ~ 40 $\mu g/m^3$, followed by industrial sources and power plants (26.5%) and agriculture (11.9%). Notably, in Delhi, the contribution of power plants and industrial sources exceeds residential emissions. With reducing the $PM_{2.5}$ concentrations to 35 $\mu g/m^3$, the WHO first interim target, premature mortality in Utter Pradash due to $PM_{2.5}$ exposure would be reduced by 76%. The total morality would be significantly reduced by lowering current $PM_{2.5}$ level to the WHO guideline value.

Thirteen scenarios based on different potential emission control strategies towards energy, residential, agriculture, industrial and open burning are simulated and compared with current emissions. If fully implemented, these measures can reduce population weighted average $PM_{2.5}$ levels by an estimated 38.7% nationwide and avoid 858,900 premature deaths annually. The

implementation of new emission standards for thermal power plants can avoid 124,000 premature deaths every year and cancelling the construction of proposed coal-fired power plants not yet under construction can avoid a further 26,000 premature deaths. A 50% reduction in the use of solid fuels by households nationwide could avoid an estimated 177,000 premature deaths annually, completely abandoning crop burning can avoid 55,000 premature deaths, reducing the use of diesel generators by 90% can avoid 30,000 premature deaths per year. The detailed reduction information was listed in Table 1.

Table 1. Potential reduction of population weighted $PM_{2.5}$ concentration ($\mu g/m^3$) and premature mortality (10^4 deaths) under certain emission scenarios with compliance in future.

Scenario	Measure	Compliance in future	Reduction of population weighted $PM_{2.5}$ concentration ($\mu g/m^3$)	Reduction of premature mortality (10^4 deaths)
1	Implement emission standards on current operating coal-based power plants		1.83	11.05
2	Implement emission standards on under-construction coal-based power plants		-0.72	-1.38
3	Avoided emissions from cancellation of new coal-fired power plants		-1.72	-2.62
4	Reduce solid fuels*	1	2.27	17.69
5	Reduce crop burning	1	0.96	5.48
6	Reduce municipal solid waste	0.8	0.8	4.55
7	Apply Bharat standards		0.91	4.73
8	Slower oil consumption growth		0.34	3.26
9	Shift to Zigzag kilns	1	1.39	8.27
10	Stronger oil sulfur limits	1	0.09	5.31
11	Introduce new emission standards	1	2.95	18.4
12	Dust control measures	0.5	0.7	4.16
13	Reduce diesel generating sets use	0.9	0.43	2.99

The results show that reducing residential emission from solid fuels combustion and reducing power sector emissions affect $PM_{2.5}$ concentration most, followed by reducing municipal solid waste burning and new emission standards applying in industry sector. In scenarios of thermal power plants emission, concentration increased maximum to more than 9 μg/m³ and decreased greatly in part of north India. From results, residential emission reduction could greatly eliminate $PM_{2.5}$ concentration, followed by implementing new emission standards in the power sector and introducing new emissions standards for the industrial sector.

New emission standards applied in industry sector affect $PM_{2.5}$ concentration the most, followed by reducing emissions from existing and new thermal power plants, reducing municipal solid waste burning and reducing residential emission from solid fuels combustion and diesel generating sets use.

Contents

1. Introduction

Increased population coupled with rapid growth of industries and urbanization has led to significant air pollution in the world. The situation is more alarming in developing Asian countries like India and China, which together house 36.5% of the world's population (UN, 2015). In comparison to China, while studies are limited, air quality is worse in India. For example, according to World Health Organization (WHO)'s reports, 15, 21 and 18 Indian cities featured in top 50 worst polluted cities with PM_{10} in 2011, 2014 and 2016, while China had 5, 1 and 5, respectively (WHO, 2011, 2014, 2016). Such high concentrations of air pollutants led to enormous pre-mature mortality in India (Chhabra et al., 2001; Dholakia et al., 2014; Maji et al., 2017; Sahu and Kota, 2017). Outdoor PM ranked the seventh in causes of death in India during 1990-2010 (IHME, 2013). In 2010, out of 3.3 million global deaths due to outdoor $PM_{2.5}$, 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 $PM_{2.5}$ concentrations. For example, annual $PM_{2.5}$ concentrations in New Delhi was 153 μg/m^3 in 2014, more than 10 times higher than in Washington DC (WHO, 2014). Controlling PM2.5 concentrations can reduce the deaths significantly.

Contributions of different sources are important information for policy makers to formulate effective emission control strategies. 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 $PM_{2.5}$ of New Delhi, and their fractional contributions are strongly dependent on seasons. Mandal et al. (2014) indicated that major parts of carbonaceous aerosols in $PM_{2.5}$ 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 $PM_{2.5}$ as secondary aerosols, soil dust, vehicle emissions, biomass burning and fossil fuel combustion in New Delhi. These statistical methods are useful to understand the sources of $PM_{2.5}$ at receptor locations, but the results are strongly dependent on availability of $PM_{2.5}$ and its components data, and sometimes challenging to resolve sources to secondary components.

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 $PM_{2.5}$ 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. 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/CIT model, Zhang and Ying (2010) found that road dust, diesel engines, internal combustion engines and coal burning are the major sources for PPM, EC, primary organic carbon (POC) and SO4 in Southeast Texas. Zhang et al. (2012) used the source-oriented Community Multiscale Air Quality model (CMAQ) and observed that power generation

is the important source for SO_4 and NO_3 in China. Similar analysis by Hu et al. (2015) discovered that residential/industrial emissions from local and Hebei accounted for more than 90% of PPM 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.

Many studies have been done to estimate the health effect caused by heavy air pollution in global scale and in some regions with enhanced resolution regional and global models and satellite data applied. In Lelieveld et al. (2015)'s work, the global premature mortality of chronic obstructive pulmonary disease (COPD), cerebrovascular disease (CEV), ischemic heart disease (IHD), lung cancer (LC) was calculated based on $PM_{2.5}$ prediction of a global atmospheric chemistry model. Also similar research has been done in high $PM_{2.5}$ concentration areas, the premature mortality caused by $PM_{2.5}$ concentration and different sources' contribution was estimated based on validated source-oriented Community Multiscale Air Quality (CMAQ) modeling results in 2013 of China (Hu et al., 2017). The results shows industrial and residential sources were the two leading sources of premature mortality, contributing to 0.40 (30.5%) and 0.28 (21.7%) million deaths, respectively. The year of life lost was also an important indicator for health effect except premature mortality. For example, Fann et al. (2012) quantified the burden of modeled concentrations of $PM_{2.5}$ on health effects in the United States of 2005 and found nearly 1.1 million life years lost from $PM_{2.5}$ exposure.

2. Methods

2.1 Model description

The CMAQ v5.0.2 model system developed by the U.S. EPA Atmospheric Science Modeling Division was used in this study to simulate air quality in India. The photochemical mechanism used in this study is SAPRC-11 (Carter, 2011) and aerosol chemistry mechanism is AERO6.

The original model was modified to conduct source contributions to different $PM_{2.5}$ components. Sources of primary PM (PPM) was conducted using a source-oriented version (CMAQ-PPM) based on CMAQ v5.0.1 using SAPRC-99 photochemical mechanism (Carter, 2000; Ying et al., 2015) and AERO6 aerosol module was expanded to trace the source type and source region. In the CMAQ-PPM model, tagged non-reactive PM tracers that bear the source type and region information are used to study the regional distributions of PPM and its chemical components from multiple emission source types and regions (Hu et al., 2015). Emissions from 9 source regions and 8 source types can be tracked simultaneously. The source apportionment of sulfate, ammonia and nitrate were quantified using a source-oriented version of CMAQv4.7.1 with SAPRC-99 photochemical mechanism and AERO5 aerosol module based on reactive tracer method. The CMAQ model tracks emissions of NO, NO_2, NH_3, and SO_2 from different emission sectors, and their corresponding reaction products in the gas and aerosol phases (Qiao et al., 2015).

The models used in this study were based on CMAQ 5.0.1 with the SAPRC11 photochemical mechanism and aerosol module version 6 (AERO6). The CMAQ model was modified to include heterogeneous formation of SO_4, NO_3, and SOA formation from surface uptake (Hu et al., 2016;

Ying et al., 2015). Source contributions of PPM and its chemical components were estimated using tagged non-reactive PPM 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 PPM 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 PPM components concentrations using E1:

$$C_{i,j} = PPM_i \times A_{i,j} \tag{E1}$$

where $C_{i,j}$ is component j concentration from source i, PPM_j is the concentration of total PPM from source i, and $A_{i,j}$ is the ratio of j component in PPM 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 SO_2, NOx, and NH_3 through atmospheric processing using tagged reactive tracers. Both the photochemical mechanism and aerosol module were expanded so that SO_4, NO_3, and NH_4 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 NO_2 reaction with hydroxyl radical (OH) in original CMAQ (R1) to source-oriented version (R2 and R3).

$$NO_2 + OH \rightarrow HNO_3 (g) \leftrightarrow NO_3^- \tag{R1}$$

In original CMAQ, HNO_3 (g) and NO_3^- are nitric acid gas and nitrate in PM.

$$NO_2\_X1 + OH \rightarrow HNO_3\_X1(g) \leftrightarrow NO_3^-\_X1 \tag{R2}$$

$$NO_2\_X2 + OH \rightarrow HNO_3\_X2(g) \leftrightarrow NO_3^-\_X2 \tag{R3}$$

In the source-oriented CMAQ, NO_2 is expanded to two species NO_2_X1 and NO_2_X2, representing the emissions from two sources. R1 is then expanded to R2 and R3. $NO_3^-\_X1$ and $NO_3^-\_X2$ represent the contributions of NO_2 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).

2.2 Health analysis

The relative risk (RR) for causes of premature mortality (COPD, CEV, IHD and LC) associated with long-term exposure of PM2.5 concentration can be calculated using integrated exposure response function as Burnett et al. (2014) described in E2 and E3.

$$RR = 1, \quad for\ c < c_{cf} \tag{E2}$$

$$RR = 1 + \alpha \left\{ 1 - \exp \left[-\gamma \left(c - c_{cf} \right)^{\delta} \right] \right\}, \quad for\ c \geq c_{cf} \tag{E3}$$

Where C_{cf} is the threshold concentration, below which we assume there is no additional risk, α, γ, δ and C_{cf} are parameters fitted for different causes based on epidemiologic data by Monte Carlo Simulations. 1000 sets of α, γ, δ and C_{cf} values for each disease were obtained from (http://ghdx.healthdata.org/sites/default/files/record-attached-

files/IHME_CRCurve_parameters.csv). C is the predicted concentration of $PM_{2.5}$ concentration. RR values were calculated for each set of α, γ, δ and C_{cf} for all people above the age of 25 and for each grid cell in our domain. And the premature mortality was calculated as E4.

$$\Delta Mort = y_o[(RR - 1)/RR]Pop \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots E4$$

Where y_o refers to baseline mortality rate for a particular disease, the baseline mortality rates for the countries were obtained from (http://www.worldlifeexpectancy.com/world-rankings-total-deaths). And Pop is the population in certain grid cell. With the 1000 RR values, the mean of 1000 premature mortality values was taken as the central value for each grid while 2.5 and 97.5 percentile were taken as lower and upper limits respectively. Overall premature mortality was calculated using by adding the average premature mortality for each disease in a grid. Total premature mortality in a state was obtained by adding all average premature mortalities of all grids in the state multiplied by the fraction of grid inside the state. A similar approach was used for calculating the upper and lower limits of premature mortality.

3. Applications

Figure 1 shows the domain we selected in India simulation in 2015. The outer 36 km domain covered the whole India and several adjacent countries and the inner 12 km domain covered areas around Delhi.
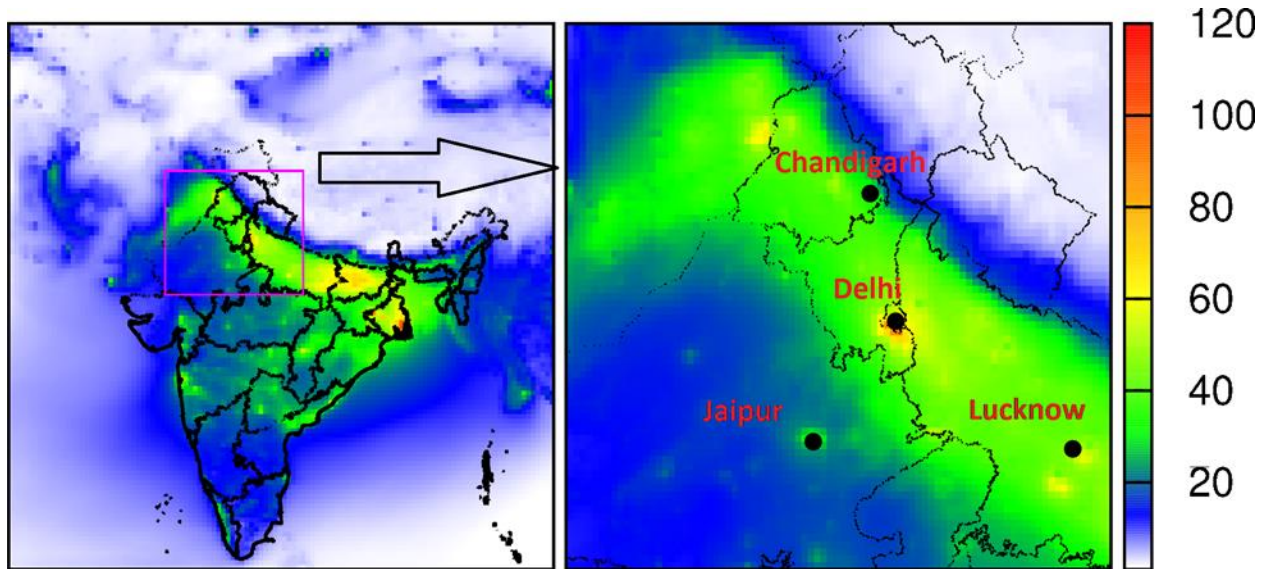

Figure 1. Domain settings in india simulation (colorbar shows $PM_{2.5}$ concentration in $\mu g/m^3$).

The Weather Research & Forecasting model (WRF) v3.7.1 was utilized to generate meteorology inputs with initial and boundary conditions from FNL (Final) Operational Global Analysis data National Center for Atmospheric Research, which is available on 1.0×1.0 degree grids continuously for every six hours (http://dss.ucar.edu/datasets/ds083.2/). The outputs of WRF were processed by Meteorology-Chemistry Interface Processor (MCIP) v4.2 to generate meteorological CMAQ inputs.

Annual anthropogenic emissions of CO, NO_x, SO_2, non-methane volatile organic compounds (NMVOC), $PM_{2.5}$, PM_{10}, EC and OC with a spatial resolution of $0.1° × 0.1°$ were downloaded from Emissions Database for Global Atmospheric Research (EDGAR) version 4.3. NMVOC and PM emissions were mapped to model species needed by the SAPRC photochemical mechanism and the AERO aerosol module. Representative profiles for each EDGAR source category were taken from the SPECIATE 4.3, a speciation profile database developed by the US EPA. The sectorial EDGAR inventories were then grouped into six broad source categories: energy, on-road transportation, off-road transportation, industries, residential activities, and agriculture as Table 2 shows and 9 regions as Figure 2 shows. Speciation was performed before the emissions were lumped into the six broad source groups. These gridded annual emissions were remapped to the CMAQ model grids. An in-house preprocessor was used to generate hourly emissions based on monthly, weekly and diurnal temporal allocation profiles. Details can be found in Wang et al. (2014) and references within. The base year of EDGAR v4.3 is 2010 and province and source specific factors based on growth and emissions control listed in Table 3-5 were used to adjust the emissions to 2015. Biogenic emissions were generated using the Model for Emissions of Gases and Aerosols from Nature (MEGAN) v2.1 (Guenther et al., 2012). The leaf area index (LAI) was based on the 8-day Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product (MOD15A2) and the plant function types (PFTs) were based on the PFT files used in the Global Community Land Model (CLM 3.0). Open biomass burning emissions were generated from the Fire Inventory from NCAR (FINN), which is based on satellite observations (Wiedinmyer et al., 2011). Windblown dust and sea salt emissions were generated in line during the CMAQ simulations. In this updated CMAQ model, windblown dust emission module was updated to be compatible with the 20-category MODIS land use data. Initial and boundary conditions for the 36km domain were based on the default vertical distributions of concentrations that represent clean continental conditions as provided by the CMAQ model, while the 36km domain provides boundary conditions for the 12km domain.. The impact of initial conditions was minimal as the results of the first five days of the simulation were excluded in the analyses.
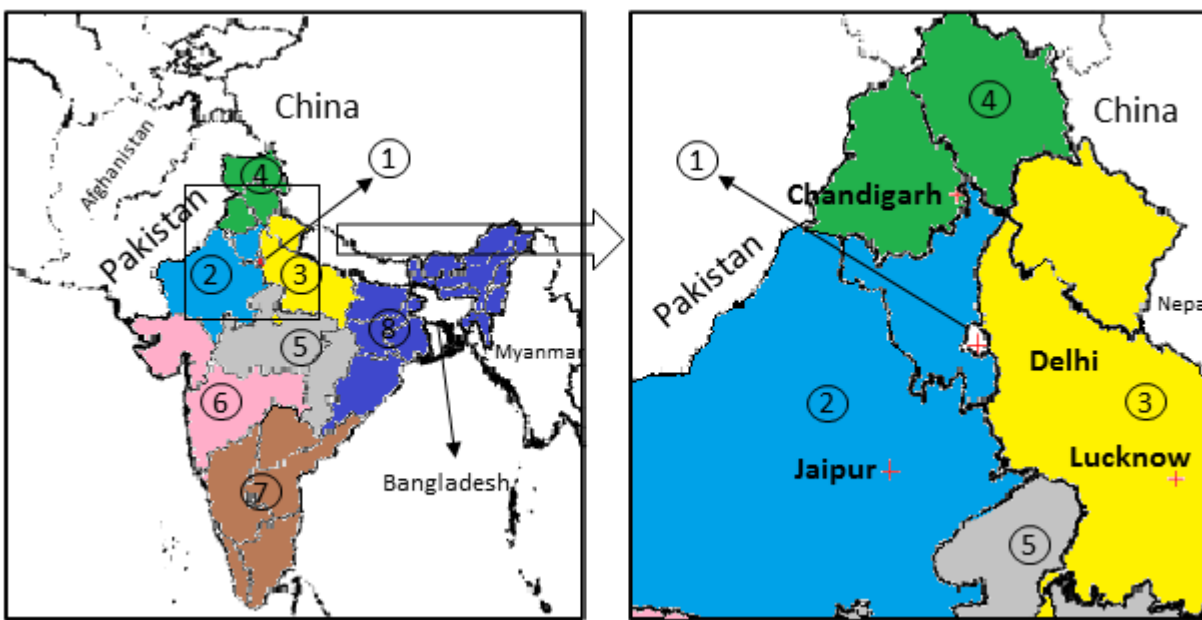

Figure 2. Source region settings in india simulation (1)Delhi, (2)Haryana & Rajasthan, (3)U.Pradesh & Uttarkhand, (4)H.Prad & Punjab, (5)Central India, (6)West India, (7)South India, (8)East & Northeast India and Outside India).

Table 2. EDGARv4.3 emission sectors and their grouping into the model source categories.

Modeling source categories	EDGARv4.3 source sectors
Energy	Power industry
Industry	Oil refineries
	Transformation industry
	Combustion for manufacturing
	Fuel exploitation
	Process emissions during production and application
	Fossil Fuel Fires
Residential	Energy for buildings
	Waste solid and wastewater
On-road	Road transportation
Off-road	Aviation climbing & descent
	Aviation cruise
	Aviation landing & take-off
	Aviation supersonic
	Railways, pipelines, off-road transport
	Shipping
Agriculture	Agriculture

Table 3. Scaling factors of energy for different states.

State	PM	VOCs	NO_x	SO_2
Andhra Pradesh	1.011	1.030	1.034	1.029
Arunachal Pradesh	1.011	1.160	1.160	1.140
Assam	1.099	1.040	1.298	1.045
Bihar	1.694	1.730	1.734	1.734
Chhattisgarh	1.643	1.800	1.813	1.799
Capital Region	0.374	1.190	0.374	0.374
Goa	1.425	0.740	0.740	0.740
Gujarat	1.425	1.600	1.631	1.595
Haryana	1.148	1.300	1.445	1.299
Himachal Pradesh	1.000	1.000	1.000	1.000
Jammu&kashmir	1.000	1.000	1.000	1.000
Jharkhand	2.166	2.220	2.219	2.217
Karnataka	1.407	1.430	1.460	1.439
Kerala	1.000	1.000	1.000	1.000
Madhya Pradesh	1.432	1.620	1.639	1.624
Maharashtra	1.268	1.460	1.479	1.455
Manipur	1.432	1.500	1.500	1.500
Meghalaya	1.022	1.030	1.066	1.031
Mizoram	1.022	1.100	1.100	1.100

Nagaland	1.022	1.230	1.230	1.230
Odisha	1.048	1.130	1.145	1.135
Punjab	0.665	0.850	0.850	0.850
Rajasthan	1.129	1.330	1.388	1.328
Sikkim	1.129	0.950	0.950	0.950
Tamil Nadu	1.858	1.960	2.002	1.959
Telangana	3.324	3.360	3.370	3.356
Tripura	1.228	1.010	1.010	1.010
Uttar Pradesh	1.228	1.340	1.358	1.343
Uttarakhand	1.341	2.020	2.024	2.024
West Bengal	1.144	1.260	1.262	1.261

Table 4. Scaling factors of On-road and Off-road for different states.

State	PM	VOCs	NO$_x$	SO$_2$
Andhra Pradesh	0.840	0.997	0.956	1.139
Arunachal Pradesh	1.004	1.197	1.181	1.379
Assam	0.857	1.017	0.969	1.159
Bihar	0.828	0.982	0.932	1.118
Chhattisgarh	0.981	1.167	1.136	1.339
Capital Region	0.922	1.114	1.310	1.337
Goa	0.661	0.777	0.674	0.864
Gujarat	0.952	1.136	1.128	1.311
Haryana	0.807	0.962	0.957	1.111
Himachal Pradesh	0.875	1.042	1.025	1.199
Jammu&kashmir	0.871	1.036	1.003	1.187
Jharkhand	0.915	1.090	1.073	1.255
Karnataka	1.010	1.203	1.187	1.385
Kerala	0.958	1.142	1.133	1.318
Madhya Pradesh	0.898	1.067	1.027	1.220
Maharashtra	0.825	0.981	0.953	1.125
Manipur	1.327	1.577	1.508	1.802
Meghalaya	0.763	0.908	0.886	1.042
Mizoram	0.981	1.168	1.144	1.343
Nagaland	0.824	0.985	1.003	1.144
Odisha	0.840	0.997	0.953	1.138
Punjab	0.798	0.951	0.948	1.099
Rajasthan	0.974	1.159	1.137	1.333
Sikkim	0.720	0.852	0.800	0.968
Tamil Nadu	0.834	0.989	0.947	1.130
Telangana	0.840	0.997	0.956	1.139
Tripura	0.805	0.956	0.916	1.093
Uttar Pradesh	0.820	0.974	0.933	1.112
Uttarakhand	0.901	1.072	1.041	1.229
West Bengal	0.814	0.967	0.932	1.106

Table 5. Scaling factors of Agriculture, Industry and Residential for nationwide.

	PM	VOCs	NOx	SO2
Agriculture	0.900	1.120	0.891	0.769
Industry	1.470	1.418	1.407	1.363
Residential	1.033	1.034	1.028	1.003

In order to test the potential effect on controlling PM$_{2.5}$ concentrations with future government controlling strategy, thirteen future emission scenarios were set up for simulation. The detailed description of scenarios is listed in Table 6.

Table 6. Description of thirteen future emission scenarios for future in India and national factor of reduce certain pollutants' emission.

Scenario	Sector	Measure	SO$_2$	NO$_x$	PM$_{10}$	PM$_{2.5}$	CO	VOC
1	Energy	Implement emission standards on current operating coal-based power plants						1*
2	Energy	Implement emission standards on under-construction coal-based power plants						2*
3	Energy	Avoided emissions from cancellation of new coal-fired power plants						3*
4	Residential	Reduce solid fuels*	-50.00%	NA	-50.00%	-50.00%	-50.00%	-50.00%
5	Agriculture	Reduce crop burning	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
6	Open-burning	Reduce municipal solid waste	-80.00%	-80.00%	-80.00%	-80.00%	-80.00%	-80.00%
7	On-road	Apply Bharat standards	NA	-24.23%	-26.71%	-26.72%	-46.05%	-82.96%
8	On-road	Slower oil consumption growth	-5.69%	-38.02%	-26.62%	-26.77%	NA	-14.91%
9	Industry	Shift to Zigzag kilns	-4.01%	-8.87%	-24.31%	-13.27%	-13.69%	NA
10	Industry	Stronger oil sulfur limits	-10.54%	NA	NA	NA	NA	NA
11	Industry	Introduce new emission standards	-54.60%	-34.20%	-78.90%	-78.90%	NA	NA
12	Construction	Dust control measures	NA	NA	-50.00%	-50.00%	NA	NA
13	Residential	Reduce diesel generating sets use	0.00%	-54.17%	-0.49%	-0.82%	-0.55%	-0.73%

1*. Calculated as: [current annual emissions] / [current average stack emission concentration] × [maximum stack emission concentration allowed by new regulation].

2*. Calculated as: [current annual emission] - [electric capacity] / [thermal efficiency] ×[plant load factor] ×[specific flue gas volume] ×[average stack emission concentration allowed by standard]

3*. Calculated as: [current annual emission] - [electric capacity] / [thermal efficiency] ×[plant load factor] ×[specific flue gas volume] ×[average stack emission concentration allowed by standard]

4. Results.

4.1 Model validation

4.1.1 Model performance of meteorological parameters

Meteorology plays an important role in transformation, emission, deposition and transport of air pollutants. In this study, wind speed (WS), wind direction (WD), temperature (T) and relative humidity (RH) predicted by the WRF model was validated using data from the National Climate Data Center (NCDC) in the simulation domain. Table 7 shows the model performance statistics of mean bias, gross error and root mean squared error, along with mean observation and prediction of the meteorological parameters for all the months in 2015. The performance of the model for different parameters were compared with the criteria suggested by Emery et al. (2001) for a model with grid sizes of 4 to 12 km. Mean bias and gross error of the predicted temperature, at 2 m, except one month, do not fall under benchmark. The model does a good job in predicting WS, which is evident from 9, 11 and 11 months falling under suggested criteria for mean bias (MB), gross error (GE) and root mean squared error (RMSE), respectively. Except 2 months for MB and 1 month for RMSE, all the months do not fall under benchmark for WD. RH is generally under-predicted except in January. Generally, WRF model performance is reliable based the comparison with previous studies mentioned above.

Table 7. Meteorology performance in all the months in 2015 (PRE is mean prediction; OBS is mean observation; MB is mean bias; GE is gross error; and RMSE is root mean square error).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T (C)	PRE	13.7	19.2	22.9	30.2	36.7	37.5	33.7	33.4	31.9	28.7	23.8	17.6
	OBS	11.1	21.2	25.2	31.8	37.2	38.6	31.5	31.7	30.0	27.0	20.9	14.5
	MB	**2.7**	**-2.0**	**-2.2**	**-1.7**	-0.5	**-1.1**	**2.2**	**1.6**	**1.8**	**1.8**	**3.0**	**3.1**
	GE	**4.0**	**2.3**	**2.7**	**2.9**	**3.8**	**4.4**	**2.6**	2.0	**2.3**	**2.2**	**3.4**	**3.3**
	RMSE	4.1	5.2	5.2	4.9	5.3	7.3	3.3	3.9	4.0	3.8	4.7	4.1
WS (m/s)	PRE	2.4	2.6	2.7	2.8	3.6	2.7	3.3	2.5	2.5	2.2	2.1	2.3
	OBS	3.1	2.9	3.5	3.6	4.0	3.1	3.0	2.4	2.7	1.9	1.5	1.8
	MB	**-0.7**	-0.3	**-0.8**	**-0.8**	-0.4	-0.4	0.2	0.1	-0.3	0.3	**0.6**	0.5
	GE	0.9	1.2	1.1	1.2	**2.2**	1.3	1.3	1.1	1.0	1.1	1.2	1.2
	RMSE	1.1	1.5	1.5	1.6	**3.3**	1.6	1.6	1.3	1.3	1.4	1.4	1.4
WD (deg)	PRE	263.4	193.7	146.1	127.7	204.6	201.3	180.2	186.6	195.1	169.1	183.8	229.9
	OBS	273.2	176.5	129.4	115.7	193.3	189.2	165.4	201.2	209.0	187.9	203.3	234.4
	MB	-9.8	**17.1**	**16.6**	**12.0**	**11.2**	**12.0**	**14.8**	**-14.6**	**-14.0**	**-18.8**	**-19.5**	-4.4
	GE	18.0	24.6	23.1	25.4	21.9	29.4	22.3	21.8	25.7	28.2	30.7	19.5
	RMSE	**32.3**	**44.0**	**46.1**	**52.8**	**48.7**	**48.2**	**43.3**	**49.4**	**48.1**	**49.9**	**41.3**	24.5
RH (%)	PRE	80.1	44.3	54.1	35.3	14.6	46.4	70.2	73.6	55.2	31.1	52.2	58.7
	OBS	78.5	47.3	55.1	38.7	18.1	49.7	74.9	76.3	58.9	36.2	59.1	66.8
	MB	1.6	-3.0	-1.0	-3.4	-3.5	-3.2	-4.6	-2.7	-3.7	-5.1	-6.9	-8.1
	GE	11.1	12.0	12.7	15.9	19.8	23.5	24.7	26.8	21.9	21.2	20.2	18.0
	RMSE	20.8	26.5	22.9	21.5	25.0	27.3	29.3	30.2	23.5	23.7	23.1	20.5

Note: Data which do not fall under the limits are shown as bold.

4.1.2. Model performance of $PM_{2.5}$

Table 8 shows the model performance of gaseous criteria pollutants $PM_{2.5}$ at eight different cities in India. All the data in a city is used for analysis. Mean observation, prediction, fractional bias (MFB), fractional error (MFE), normalized bias (MNB) and normalized error (MNE) at the eight cities is shown. Except in Kolkata, Mumbai and Hyderabad, the model slightly under-predicted the concentrations of $PM_{2.5}$. The MFB and MFE values in all cities lies in the criteria level of ±0.6 and 0.75 suggested by the EPA (USEPA, 2007). This indicates that the model performance is acceptable and the base case model can be used for regulatory applications for $PM_{2.5}$. Similar model performance in predicted $PM_{2.5}$ was observed in Ghude et al. (2016). Under-prediction is observed in Delhi, Patna, and Lucknow, while under-prediction is observed in Ahmedabad. Future studies on emissions, mechanism, and meteorology are needed to investigate this.

Table 8. Model performance of O_3, $PM_{2.5}$, CO, SO_2 and NO_2 at Delhi (DEL), Lucknow (LUC), Patna (PAT), Kolkata (KOL), Ahmadabad (AHM), Mumbai (MUM), Hyderabad (HYD), Bengaluru (BAN) and Chennai (CHE) in India during 2015. Note: OBS, PRE, MFB, MFE, MNB, MNE and No denote observation, prediction, fractional bias, fractional error, normalized bias, normalized error, and number of points.

		DEL	LUC	PAT	KOL	AHM	MUM	HYD	BAN	CHE
$PM_{2.5}$	OBS	126.6	139.4	201.7	101.8	94.3	51.4	58.3	60.3	75
	PRE	87	64.5	121.3	123.7	56.9	99.3	61.8	41	39.1
	MFB	-0.31	-0.45	-0.42	0.2	-0.38	0.49	0.03	-0.29	-0.42
	MFE	0.5	0.61	0.54	0.54	0.51	0.57	0.28	0.39	0.49
	MNB	-0.31	-0.53	-0.39	0.21	-0.39	0.92	0.06	-0.31	-0.47
	MNE	0.45	0.6	0.46	0.64	0.49	1.02	0.3	0.39	0.52
	No	6587	3626	1544	3488	1147	5254	1315	582	619

4.2 Predicted concentrations of $PM_{2.5}$ and its components

Figure 3 and Figure 4 shows the seasonal change in concentrations of total $PM_{2.5}$ and its components, respectively. Higher $PM_{2.5}$ concentrations were observed in the Indo-Gangetic plain and peaked in winter and post-monsoon. Primary components of $PM_{2.5}$, elemental carbon and primary organic aerosol (POA) were higher in winter due to increase in emissions from house hold wood burning and agricultural activities (Behera and Sharma, 2015). Higher SOA concentrations are observed in post monsoon and winter than pre-monsoon and monsoon in the country. This could be due to greater anthropogenic emissions of SOA precursors and acidity of aerosols in winter (Fu et al., 2016; Rengarajan et al., 2011). SO_4, NO_3 and NH_4 peaked in winter and post-monsoon and least during monsoon.
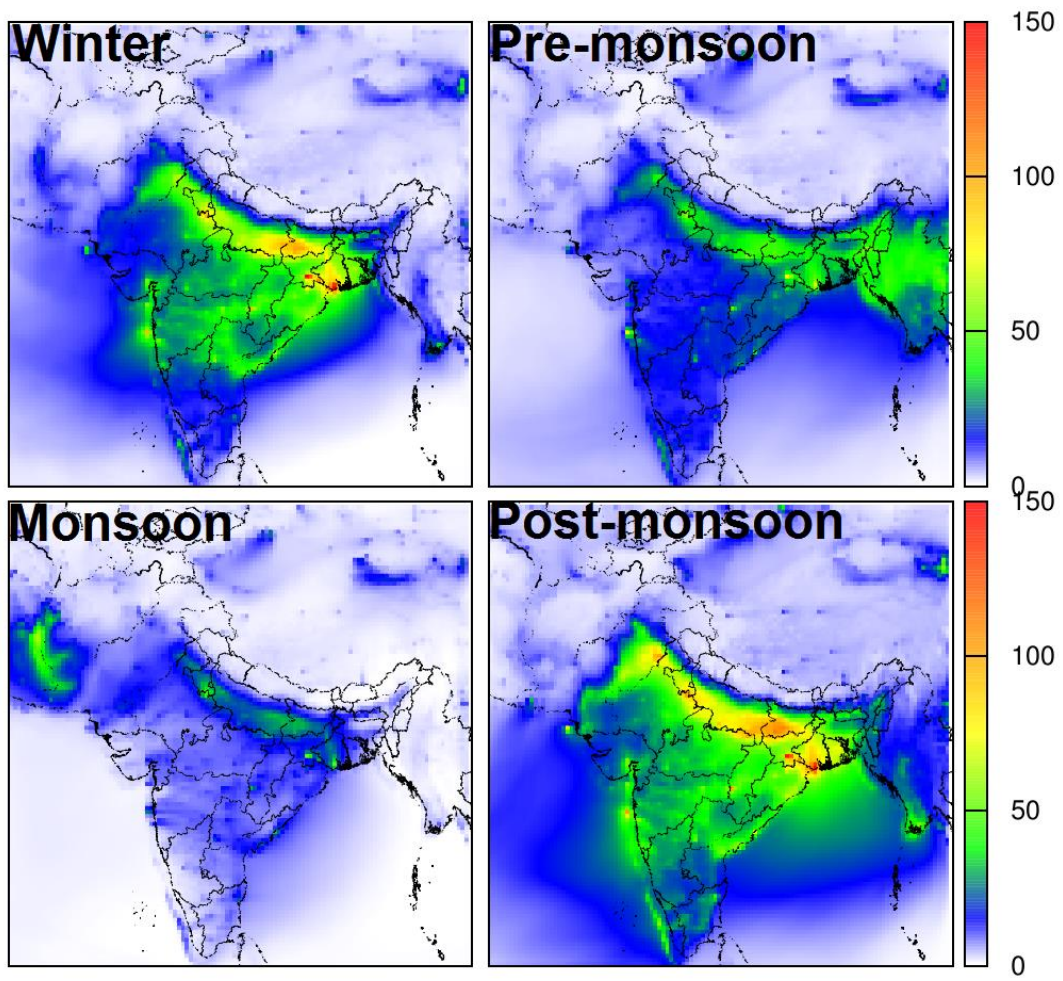
Figure 3. Seasonal variation of predicted PM$_{2.5}$ in India in 2015 (Units are in μg/m^3).
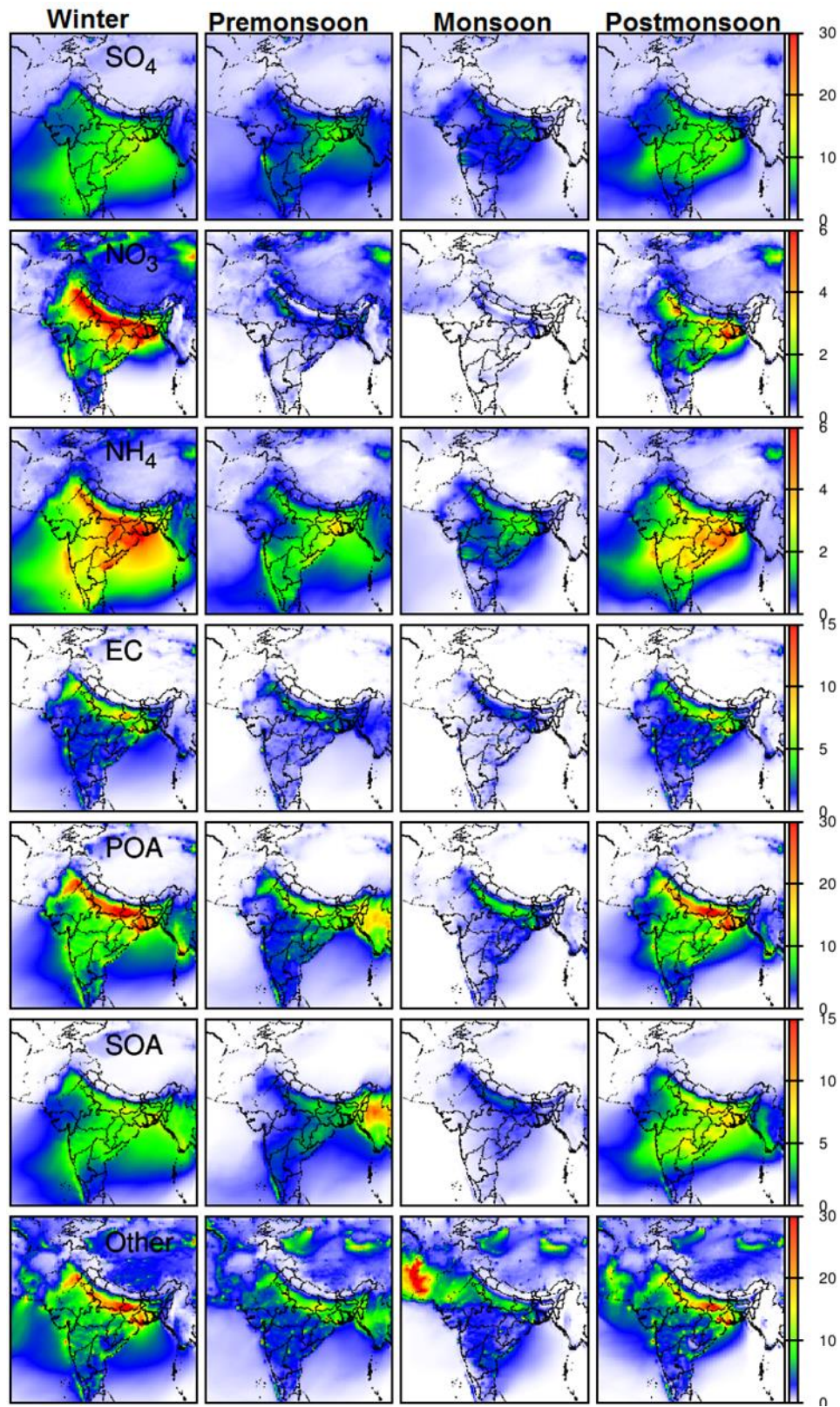
Figure 4. Seasonal variation in predicted components of PM$_{2.5}$ in India in 2015 (Units are in µg/m^3).

4.3 Source apportionment of primary PM$_{2.5}$

To better understand contribution of Primary PM (PPM) from each source type, the total PPM were divided into 8 catalogs: energy, industry, residential, on-road, off-road, agriculture, open burning (satellite detected biomass burning biomass, which includes wildfire, agricultural fires, and prescribed burning and does not include biofuel use and trash burning.) and windblown dust. Figure 5 shows the source apportionment results of PPM in 36km domain. Generally, in the severe polluted area from North India to South India, the major contributors are energy, industry, residential and agriculture. On-road and off-road transportation sector contributed 0.4 and 0.6 μg/m^3 to PPM. The small contribution may due to underestimation of EDGAR emission inventory and the coarse resolution in our simulation. Windblown dusts have a high contribution to total PPM in some areas outside India like Tibet and Iran. Figure 6 shows time series plot of source apportionment of PPM in eight cites (Amritsar, Varanasi, Gurgaon, Kanpur, Patna, Ranchi, Raipur, and Kolkata).
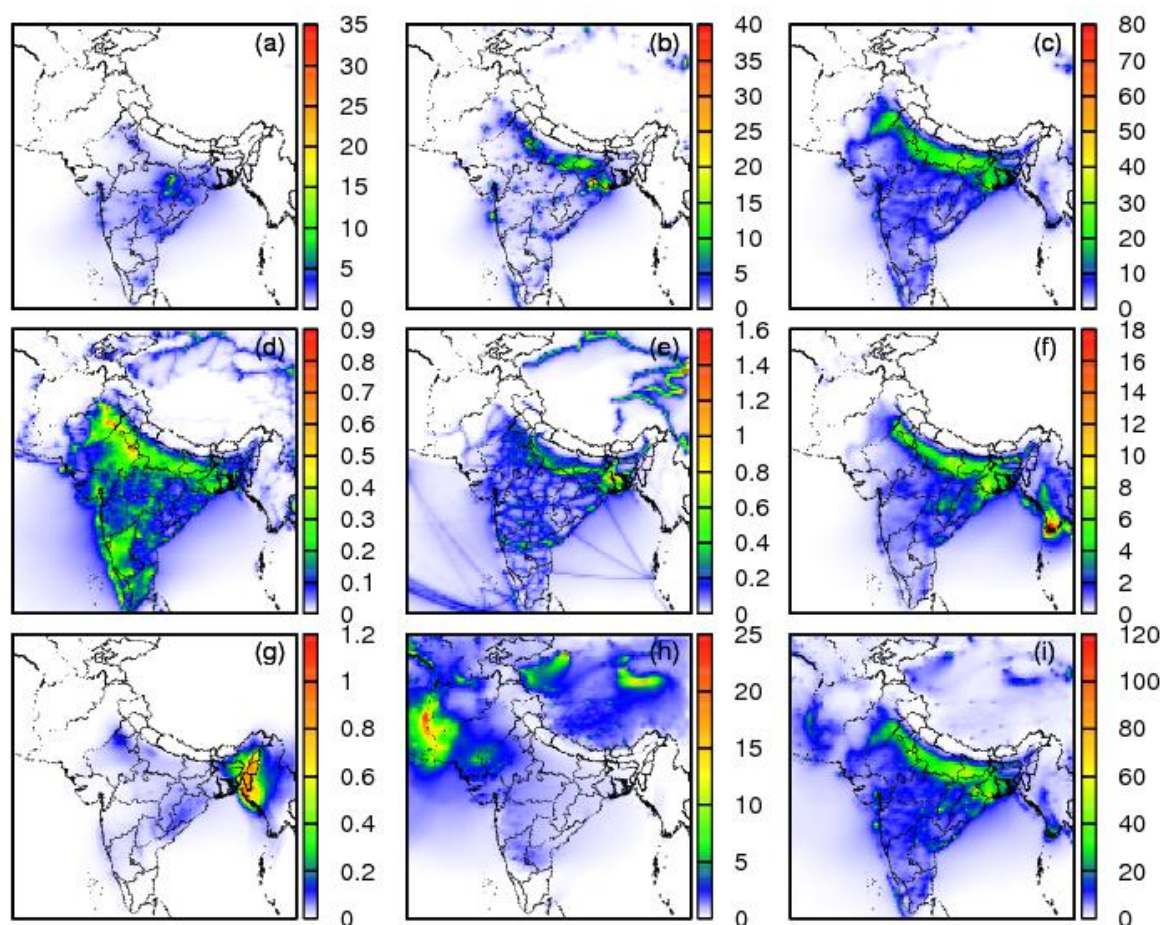
Figure 5. Source apportionment of primary PM in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, (h) windblown dust and (i) total. Units are in μg/m^3).

Similar to 36 km results, Figure 7 shows the source apportionment results of PPM in 12km domain. Also, the energy, industry and residential were the major contributors to total PPM in South Delhi. Residential and agriculture contributed a lot to total PPM at Punjab, Haryana and Parts of North Uttar Pradesh.
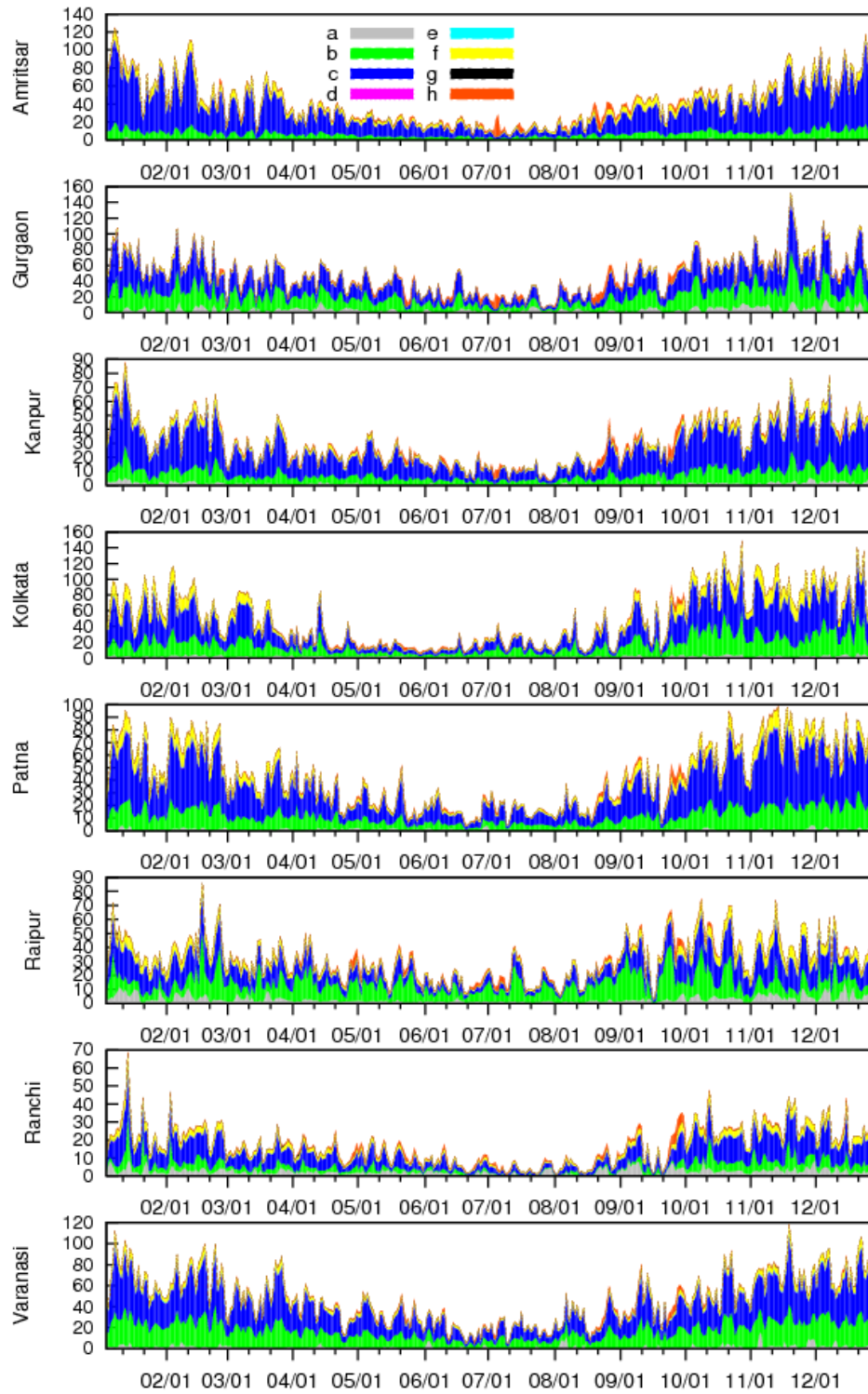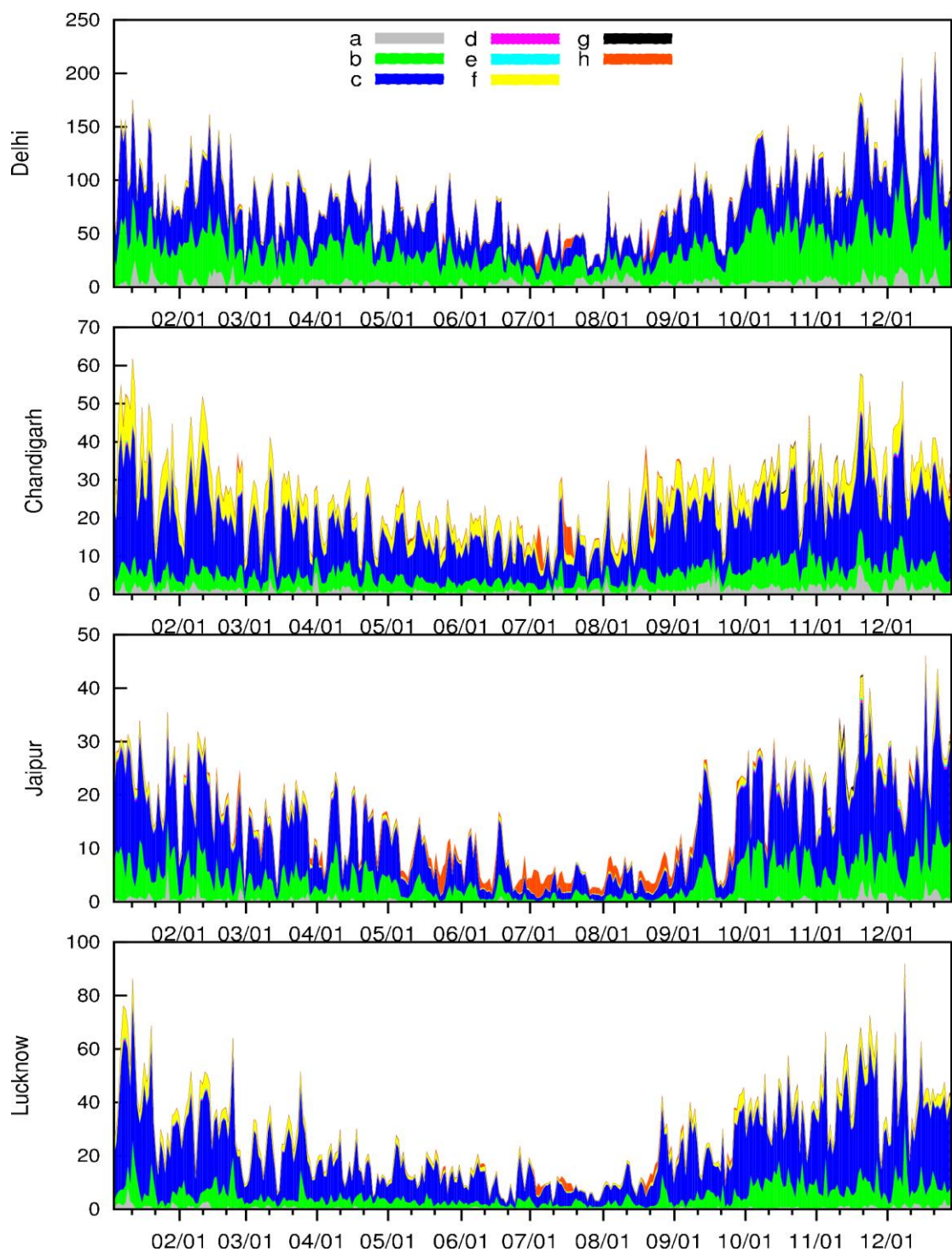
Figure 6. Time series t at specific cities in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) windblown dust. Units are in μg/m³)
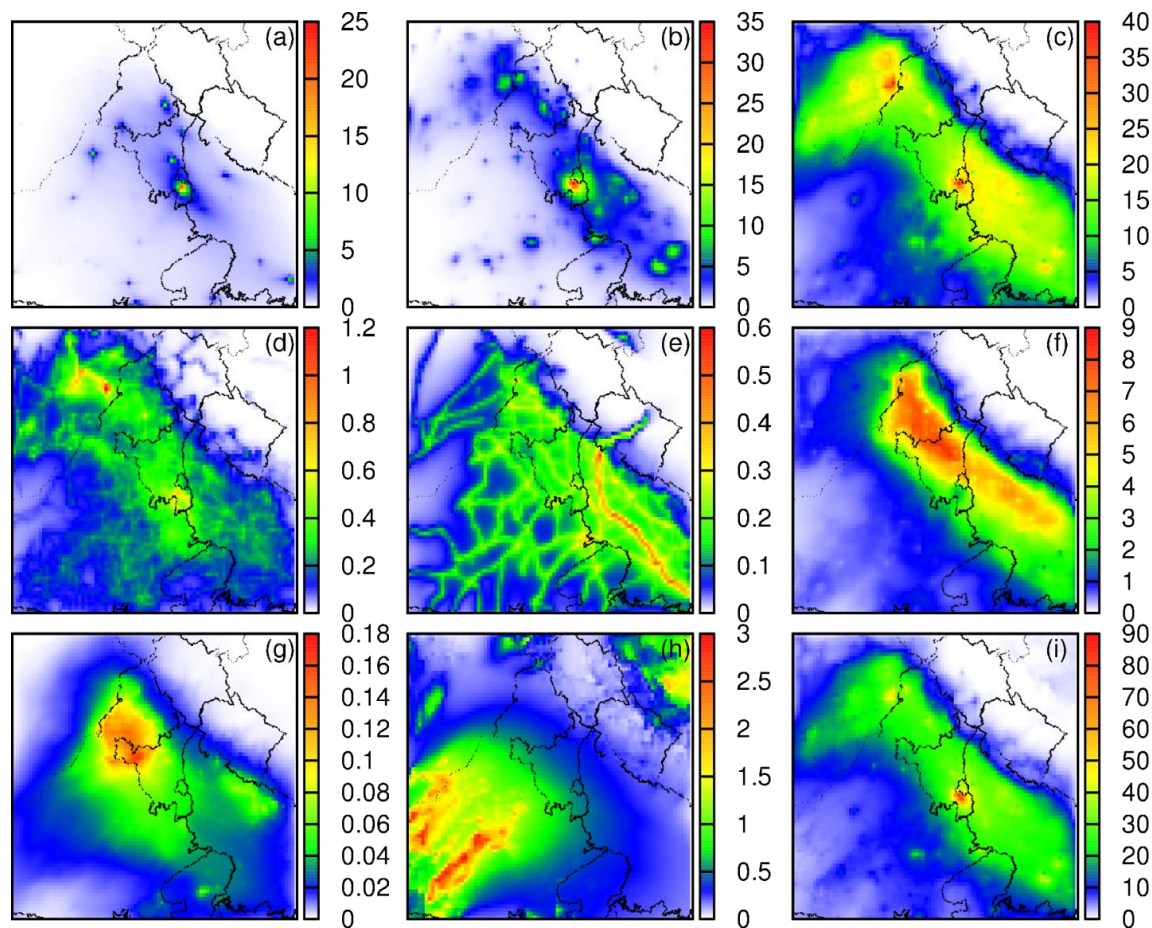
Figure 7. Source apportionment of primary PM in 12 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, (h) windblown dust and (i) total. Units are in μg/m³).

To study some important cities in Delhi and surrounding areas, Figure 8 shows time series plot of source apportionment of PPM in four cites (Delhi, Chandigarh, Jaipur and Lucknow). In all four cities, industry and residential are two major source of PPM. In Delhi and Jaipur, energy also contributes to total PPM concentration. Agriculture plays an important role in total PPM concentration at Chandigarh. The detailed percentages of each source type ratio in total PPM at four cities are shown in Table 9.

Figure 8. Time series at specific cities (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) windblown dust. Units are in µg/m³)

Table 9. Contributions of different sectors to total PPM at selected cities in 12km domain

	energy	industry	residential	On-road	Off-road	agriculture	open burning	Windblown dust
Delhi	5.52%	46.68%	44.04%	0.81%	0.36%	2.47%	0.00%	0.11%
Chandigarh	5.50%	18.09%	56.77%	1.27%	1.02%	17.19%	0.01%	0.14%
Jaipur	3.87%	30.99%	56.84%	1.72%	1.42%	4.64%	0.01%	0.51%
Lucknow	2.72%	19.97%	66.98%	0.96%	0.93%	8.28%	0.01%	0.14%

To analyze the source region, source apportionment simulations based on 9 regions (Delhi, Haryana & Rajasthan, U.Pradesh & Uttarkhand, H.Prad & Punjab, Central India, West India, South India, East & Northeast India and Outside India) of India were conducted. Figure 9 shows the regional plot of the regional source apportionment results. Uttar Pradesh, Uttarakhand, central India, West India and some parts of East and Northeast India have high PPM concentrations (up to 100μg/m^3).
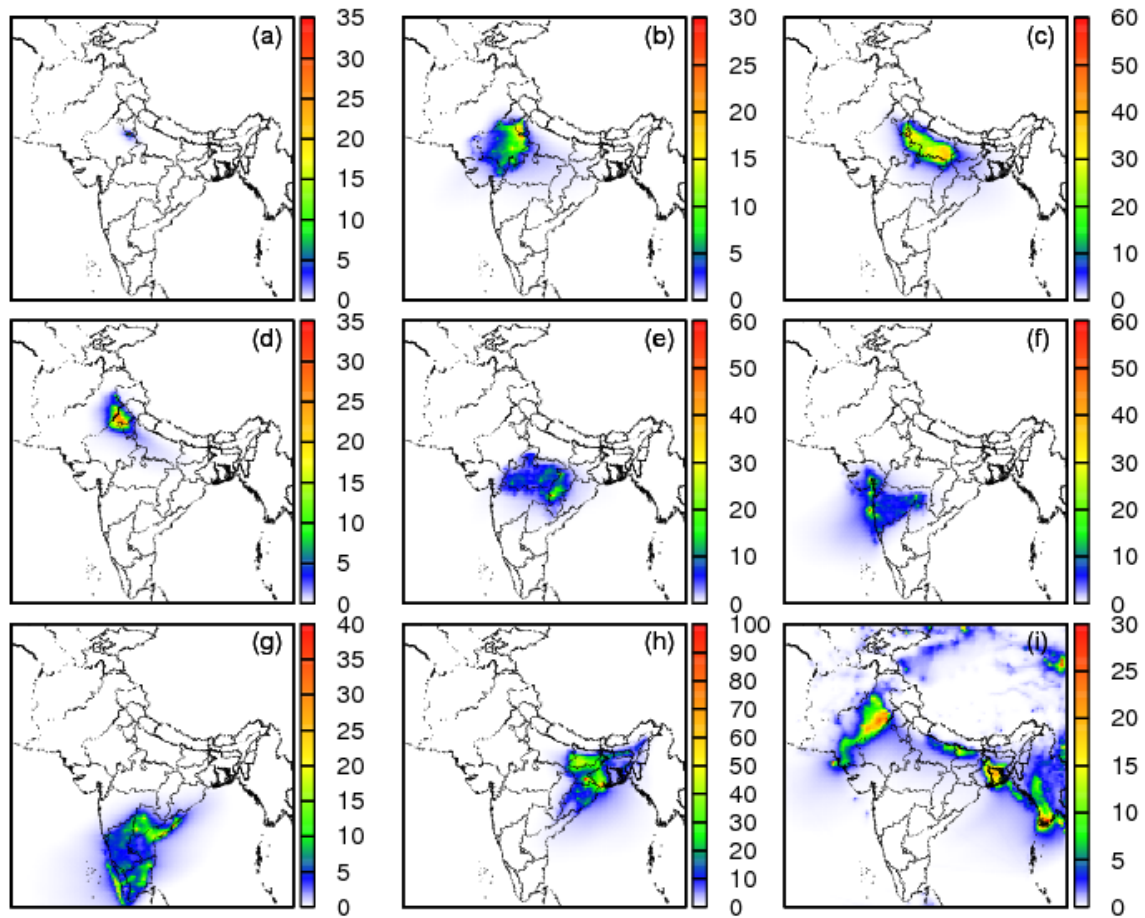
Figure 9. Source apportionment of primary PM in 36km domain based on different source regions (source regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, (f) West India, (g) South India, (h) East & Northeast India and (i) Outside India Units are in μg/m^3)

In 12 km domain, Delhi has a high concentration of PPM to 70µg/m³ as in Figure 10. Also, Uttar Pradesh, Uttarakhand, H.Prad,J.kash and Punjab have a 40µg/m³ in highest value.
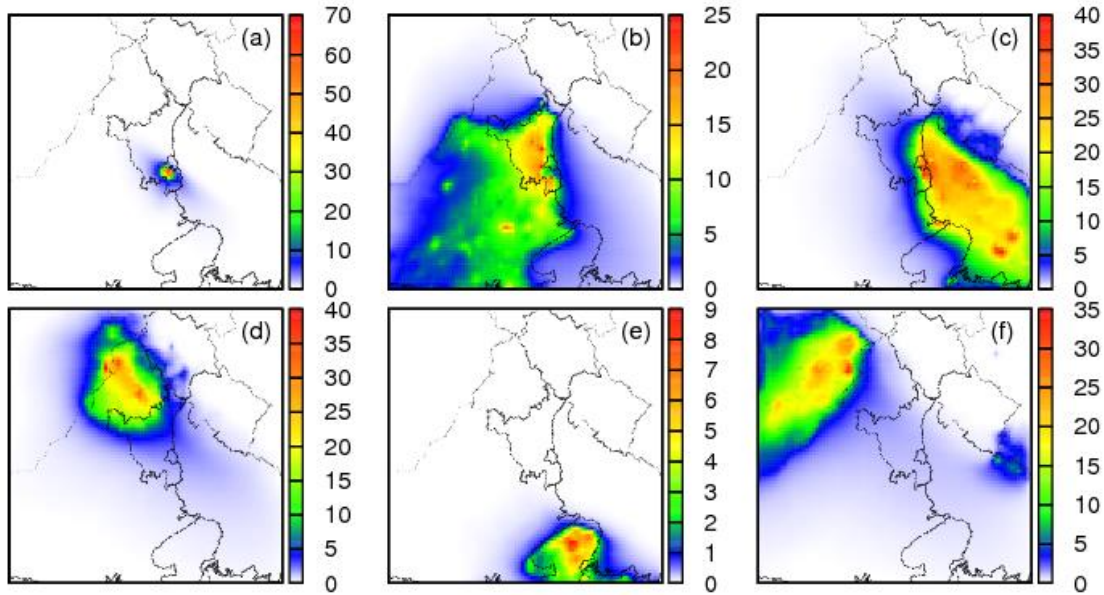
Figure 10. Source apportionment of primary PM in 12km domain based on different source regions (regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, and (f) Outside India. Units are µg/m³)

Generally, PPM concentrations of selected cities are coming from within the state sources as shown in time series plot (Figure 11) and Table 10. Chandigarh is the capital of the northern Indian states of Punjab and Haryana, Jaipur is the capital of India's Rajasthan state, and Lucknow is the capital of the state of Uttar Pradesh and Delhi. About 80% of PPMs are from within the states sources in these 4 cities.
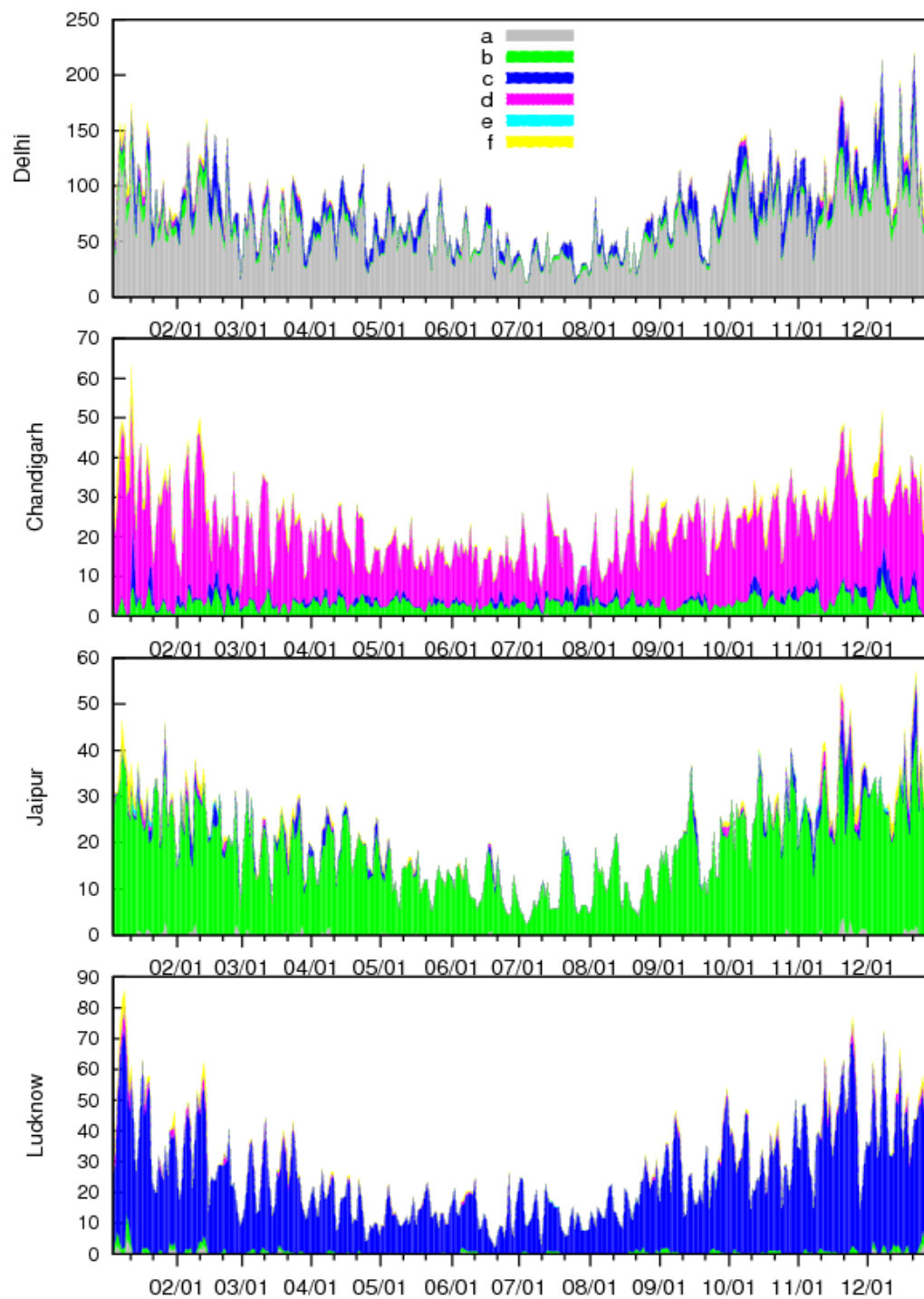
Figure 11. Time series at specific cities (sources regions are: (a) Delhi, (b) Haryana and Rajasthan, (c) U. Pradesh and Uttarakhand, (d) H. Prad, J. kash and Punjab, (e) Central India, and (f) Outside India. Units are in µg/m³)

Table 10. Contributions of different regions to total PPM at selected cities in 12km domain

	Delhi	Haryana and Rajasthan	U.Pradesh and Uttarakhand	H.Prad,J.kash and Punjab	Central India	Outside India
Delhi	73.79%	8.68%	12.65%	2.48%	0.08%	2.32%
Chandigarh	0.43%	8.77%	8.00%	77.25%	0.04%	5.52%
Jaipur	1.43%	83.18%	6.24%	2.83%	1.07%	5.25%
Lucknow	2.11%	3.96%	87.83%	3.03%	0.18%	2.89%

4.4 Source apportionment of secondary inorganic aerosols

4.4.1 Source apportionment of ammonia

To study contributions of ammonia PM from each source type, the ammonia PM were separated into 8 catalogs: energy, industry, residential, on-road, off-road, agriculture, wildfire and background. Figure 12 shows the source apportionment results of ammonia PM in 36km domain. Residential and agriculture contribute almost all the ammonia PM, especially at the high concentration area from North India to South India. Figure 13 shows time series plot of source apportionment of ammonia in eight cites (Amritsar, Varanasi, Gurgaon, Kanpur, Patna, Ranchi, Raipur, and Kolkata).
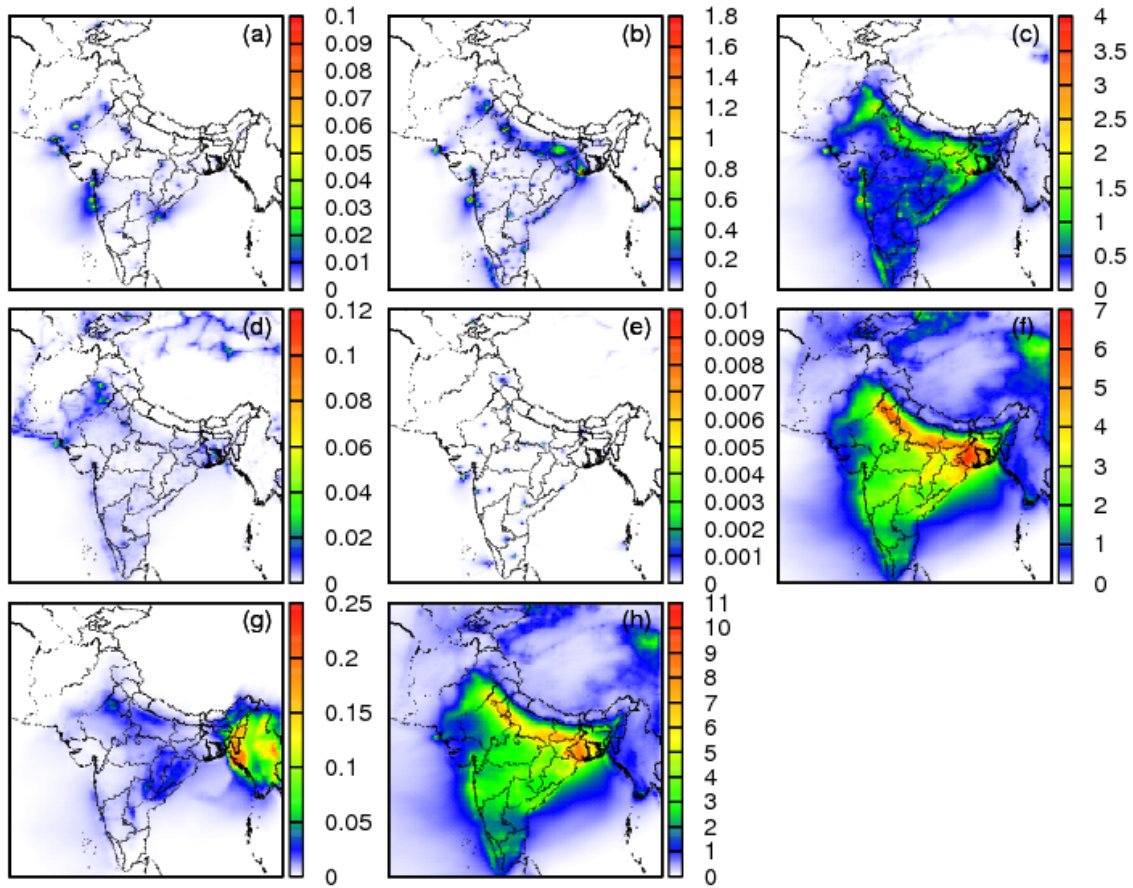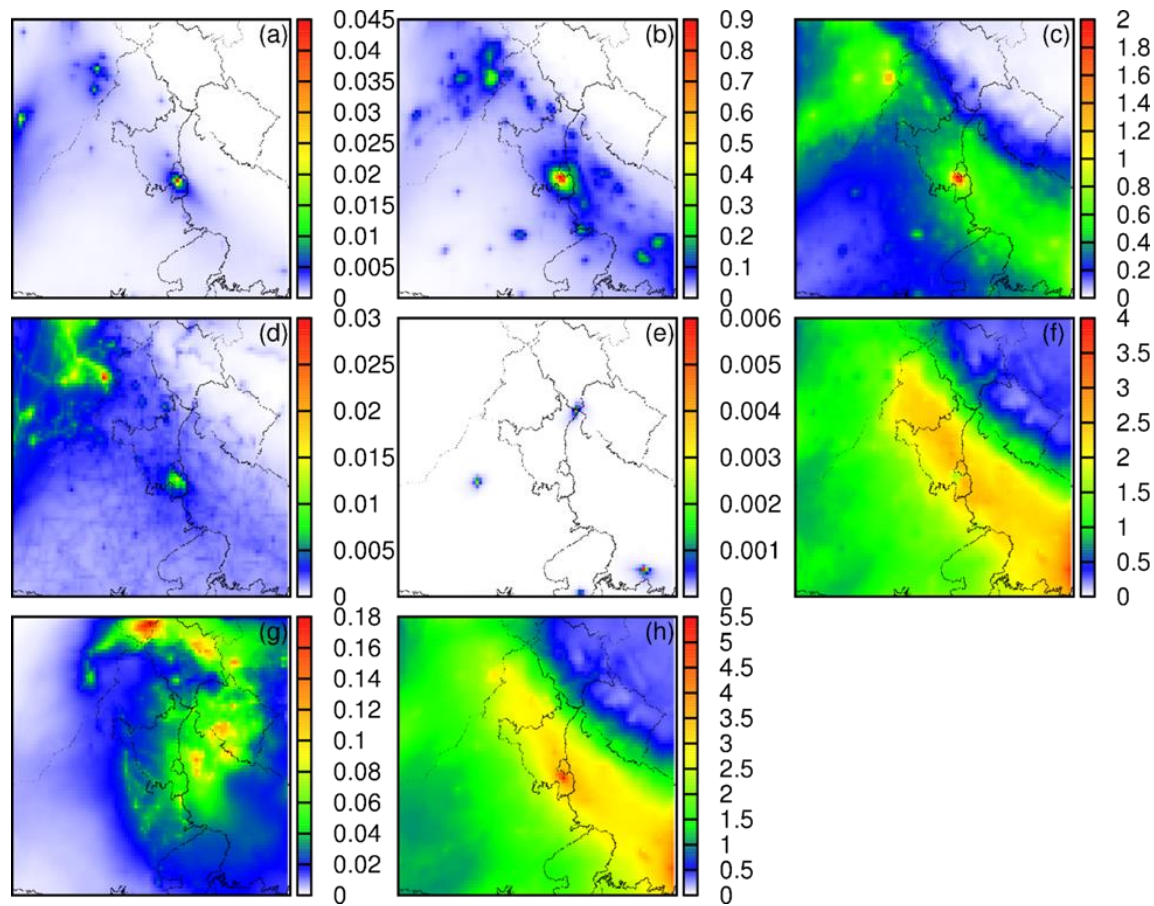

Figure 12. Source apportionment of NH$_4$ in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) total. Units are in μg/m3. As windblown dust does not contribute to ammonia, it is not included).
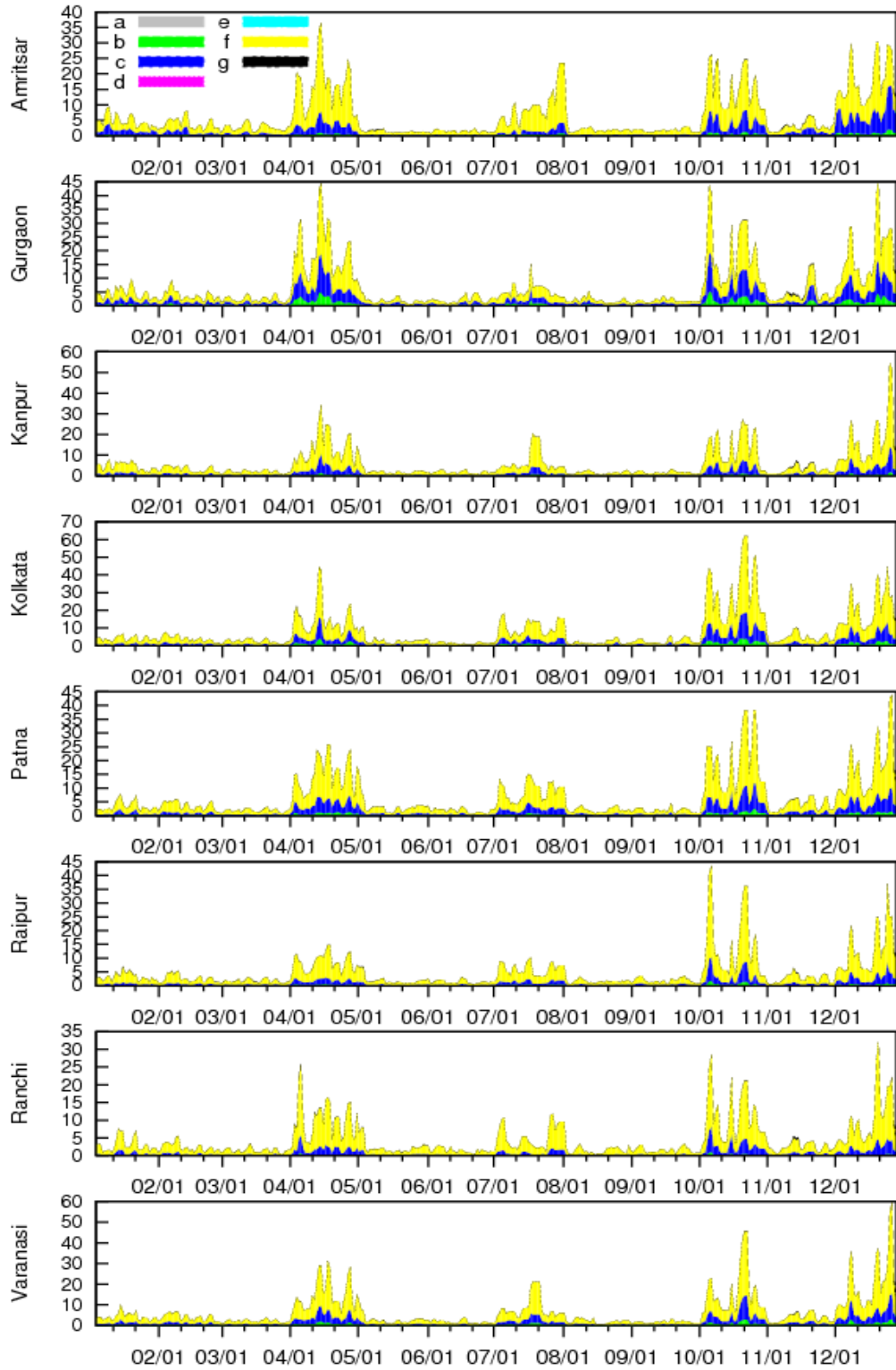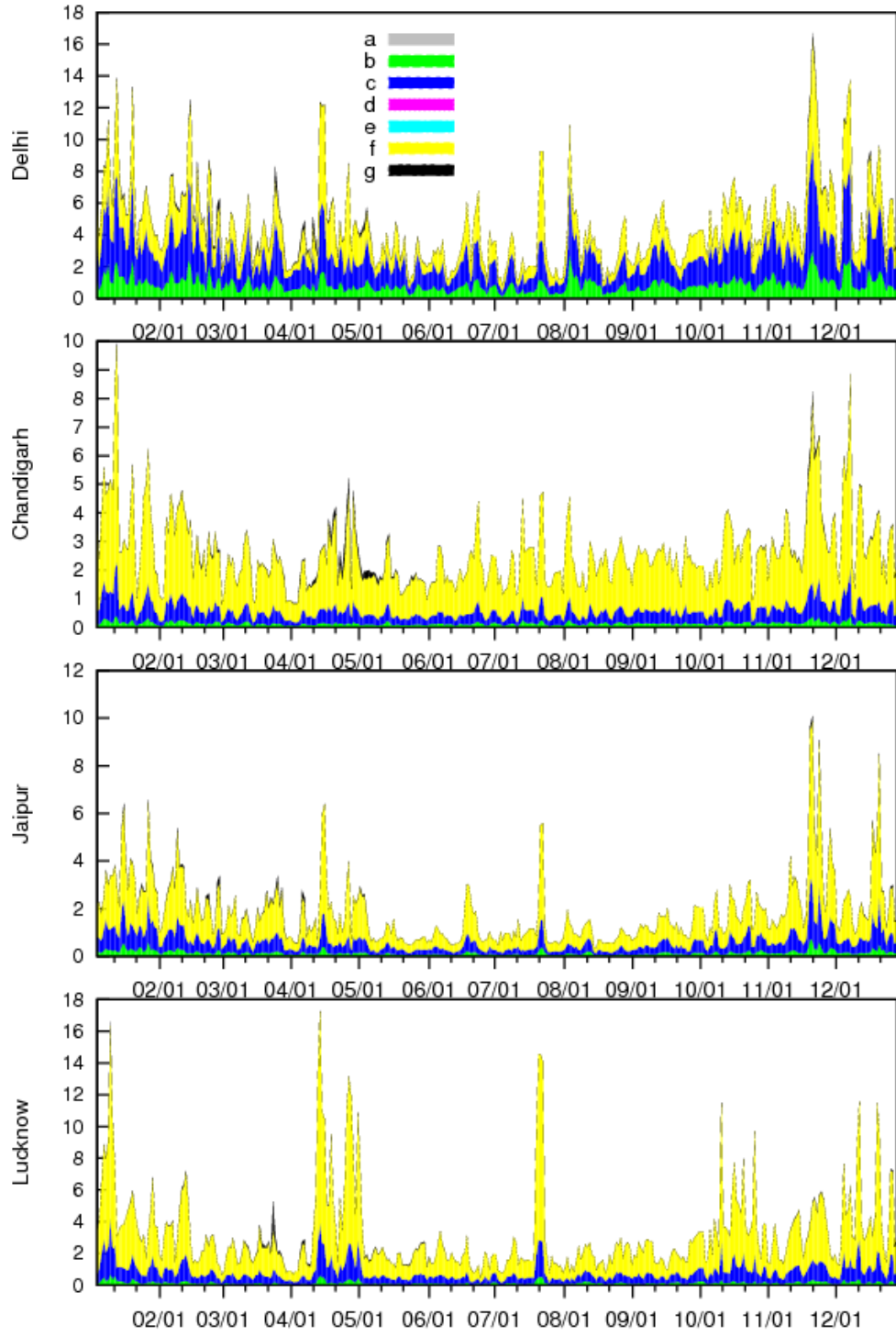
Figure 13. Time series at specific cities in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, and (g) open burning. Units are in µg/m³).

Figure 14 of 12 km source apportionment results of ammonia PM demonstrate that high residential ammonia PM concentrations in South Delhi and high agriculture ammonia PM concentrations in Haryana and Parts of North Uttar Pradesh should be the major contributors to total ammonia PM.

Figure 14. Source apportionment of NH₄ in 12-km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) total. Units are in μg/m³. As windblown dust does not contribute to ammonia, it is not included).

Similar results are obtained from time series source apportionment results of ammonia PM at the four cities in Figure 15. The residential and agriculture dominate the ammonia PM and other source types can be neglected, although industry also contributes to total ammonia PM at Delhi. The detailed percentages of each source type ratio in total ammonia PM at four cities are shown in Table 11.

Figure 15. Time series at specific cities (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, and (g) open burning. Units are in µg/m³)

Table 11. Contributions of different source sectors to ammonia at selected cities

	energy	industry	residential	On-road	Off-road	agriculture	open burning
Delhi	0.17%	17.80%	43.78%	0.18%	0.00%	37.25%	0.83%
Chandigarh	0.03%	1.78%	16.07%	0.09%	0.00%	81.31%	0.72%
Jaipur	0.02%	4.16%	20.08%	0.10%	0.00%	74.46%	1.18%
Lucknow	0.03%	2.81%	21.71%	0.06%	0.00%	74.83%	0.55%

Same as PPM analysis, source apportionment of ammonia PM simulations based on 9 regions of India were conducted. Figure 16 shows the regional plot of the regional source apportionment results. East and Northeast India have highest ammonia PM concentrations (up to 6 µg/m³)
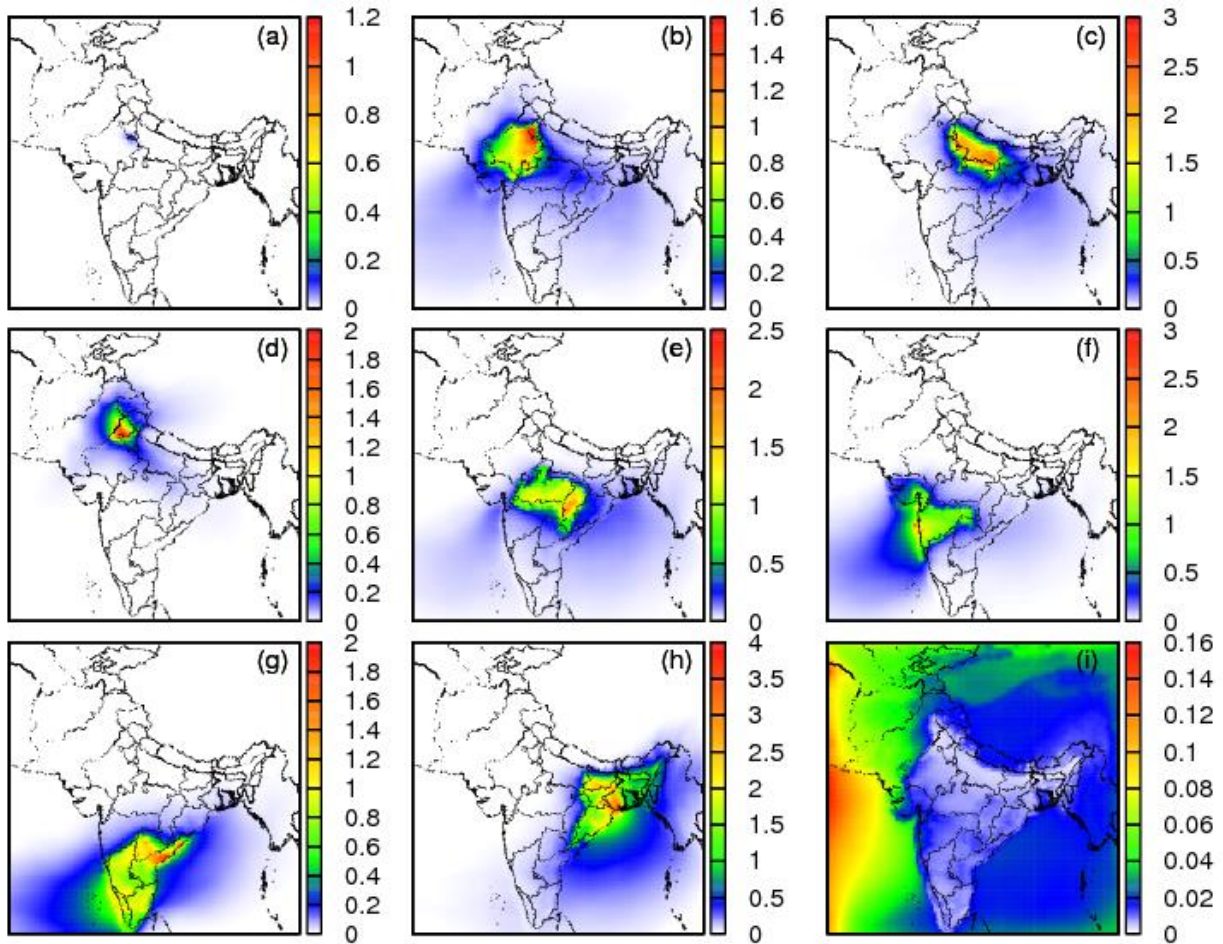
Figure 16. Source apportionment of ammonia PM in 36km domain based on different source regions (source regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, (f) West India, (g) South India, (h) East & Northeast India and (i) Outside India Units are in µg/m³)

In 12 km domain, the entire region mainly have a highest ammonia PM concentration of 2.5 µg/m^3 as in Figure 17.
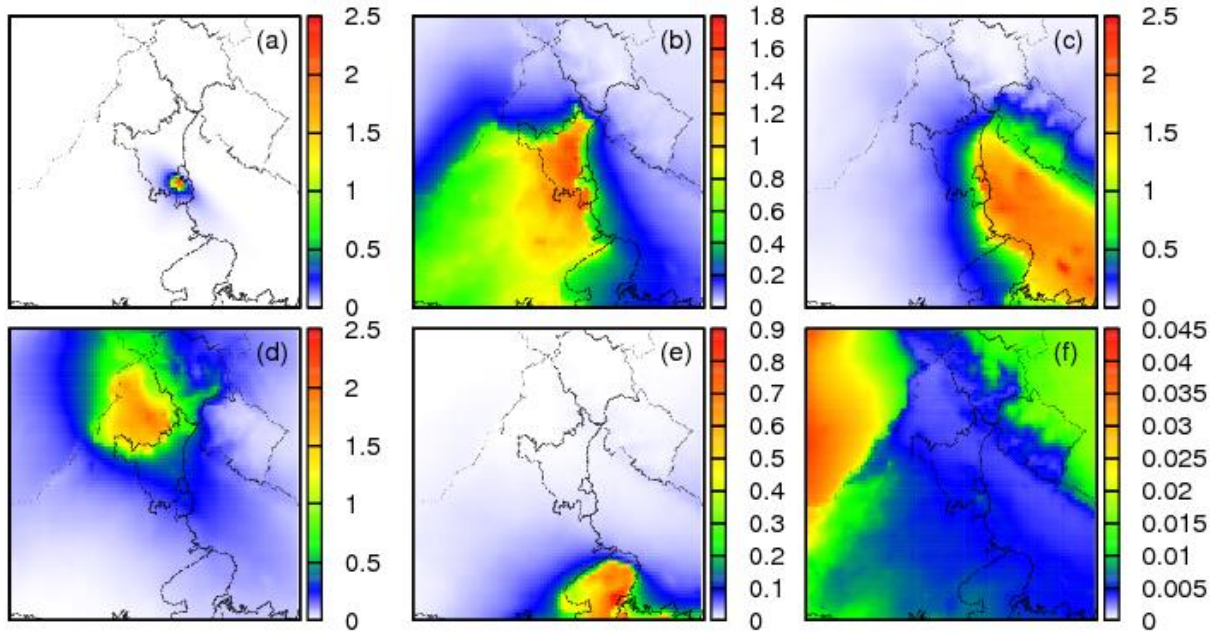
Figure 17. Source apportionment of ammonia PM in 12km domain based on different source regions (source regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, and (f) Outside India Units are in µg/m³)

Similar to PPM analysis, 80% of the total ammonia PM concentrations are from within the state, but Delhi have 20% of the total ammonia PMs coming from the adjacent state: Haryana, Rajasthan, U.Pradesh and Uttarakhand as the time series plot in Figure 18 and Table 12 shows.
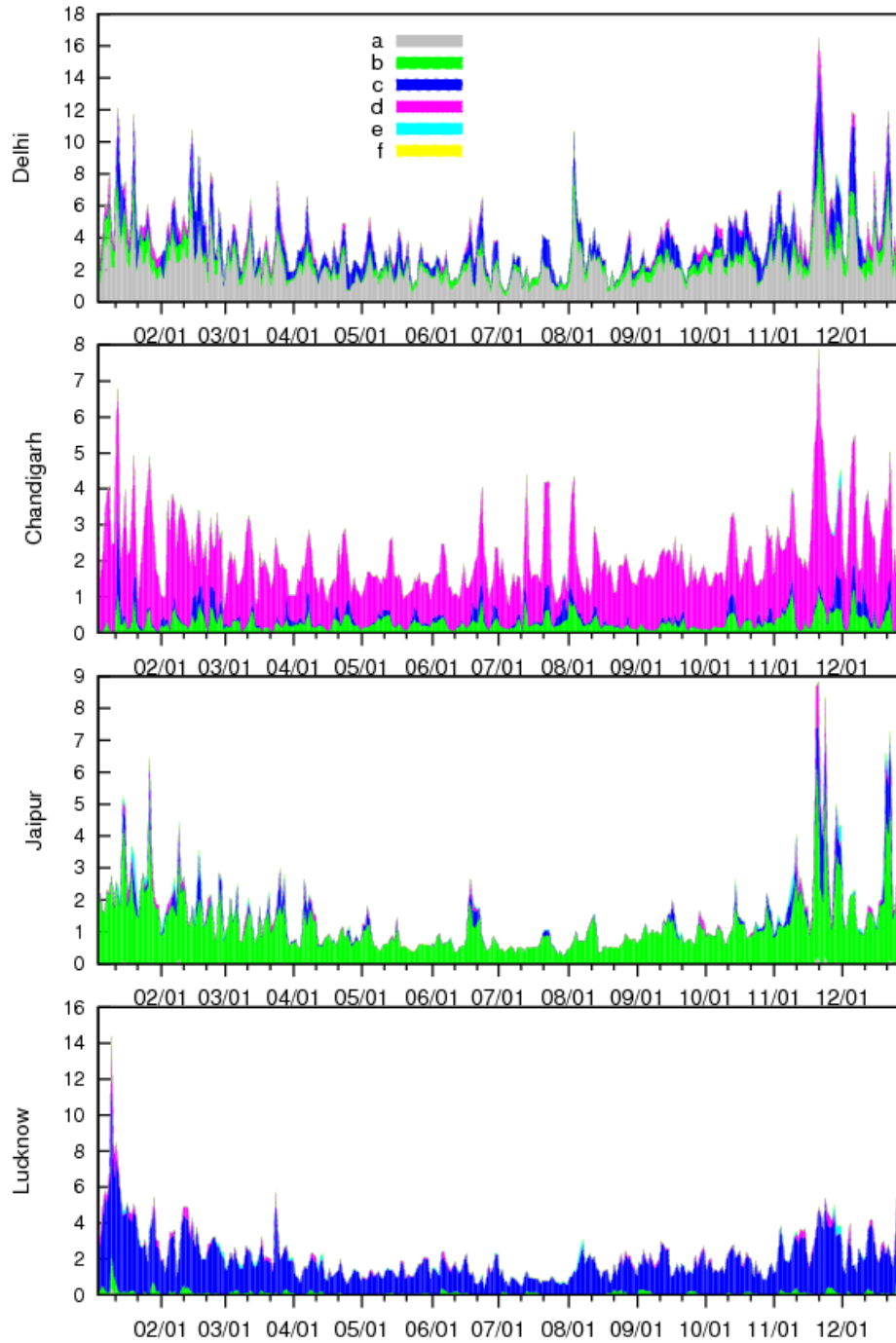
Figure 18. Time series plot at specific cities (sources regions are: (a) Delhi, (b) Haryana and Rajasthan, (c) U.Pradesh and Uttarakhand, (d) H.Prad, J.kash and Punjab, (e) Central India, (f) Outside India)

Table 12. Contributions of different regions to total PPM at selected cities in 12km domain

	Delhi	Haryana and Rajasthan	U.Pradesh and Uttarakhand	H.Prad,J.kash and Punjab	Central India	Outside India
Delhi	52.54%	18.23%	19.24%	9.66%	0.23%	0.10%
Chandigarh	0.09%	11.33%	9.91%	78.35%	0.19%	0.13%
Jaipur	0.60%	80.92%	11.35%	3.80%	3.09%	0.23%
Lucknow	0.87%	7.05%	83.36%	8.07%	0.48%	0.18%

4.4.2 Source apportionment of nitrate

The same catalogs with above are used in analyzing source apportionment of nitrate PM in India. Figure 19 shows the source apportionment results of nitrate PM in 36km domain. Energy, industry and on-road contribute almost of nitrate PM especially at the high concentration area from North India to South India. Different with ammonia PM, energy nitrate PM concentrations are also high in Central India. Figure 20 shows time series plot of source apportionment of nitrate in eight cites (Amritsar, Varanasi, Gurgaon, Kanpur, Patna, Ranchi, Raipur, and Kolkata).
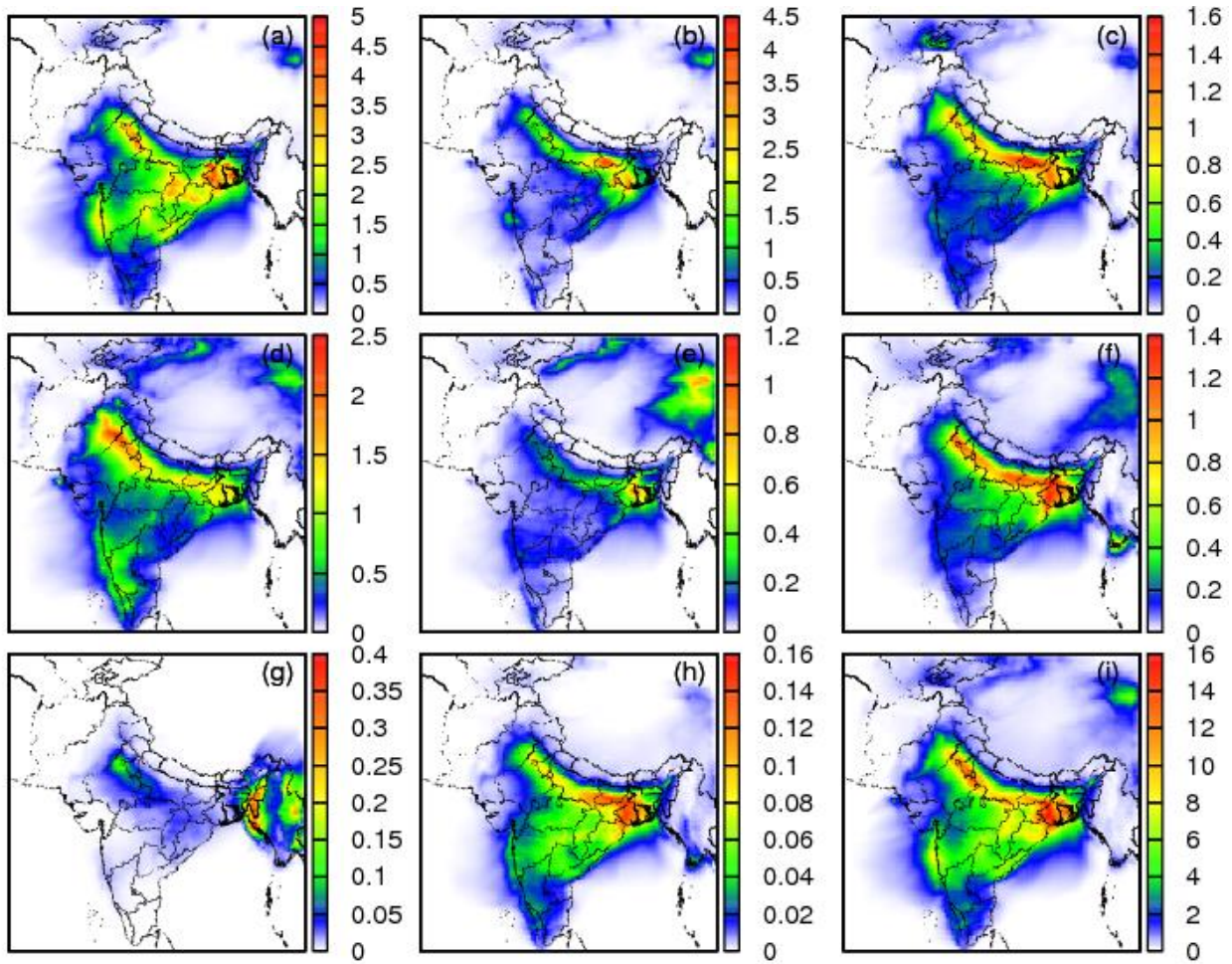
Figure 19. Source apportionment of NO₃ in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f)agriculture, (g) open burning, (h) windblown dust and (i) total. Units are in μg/m³)
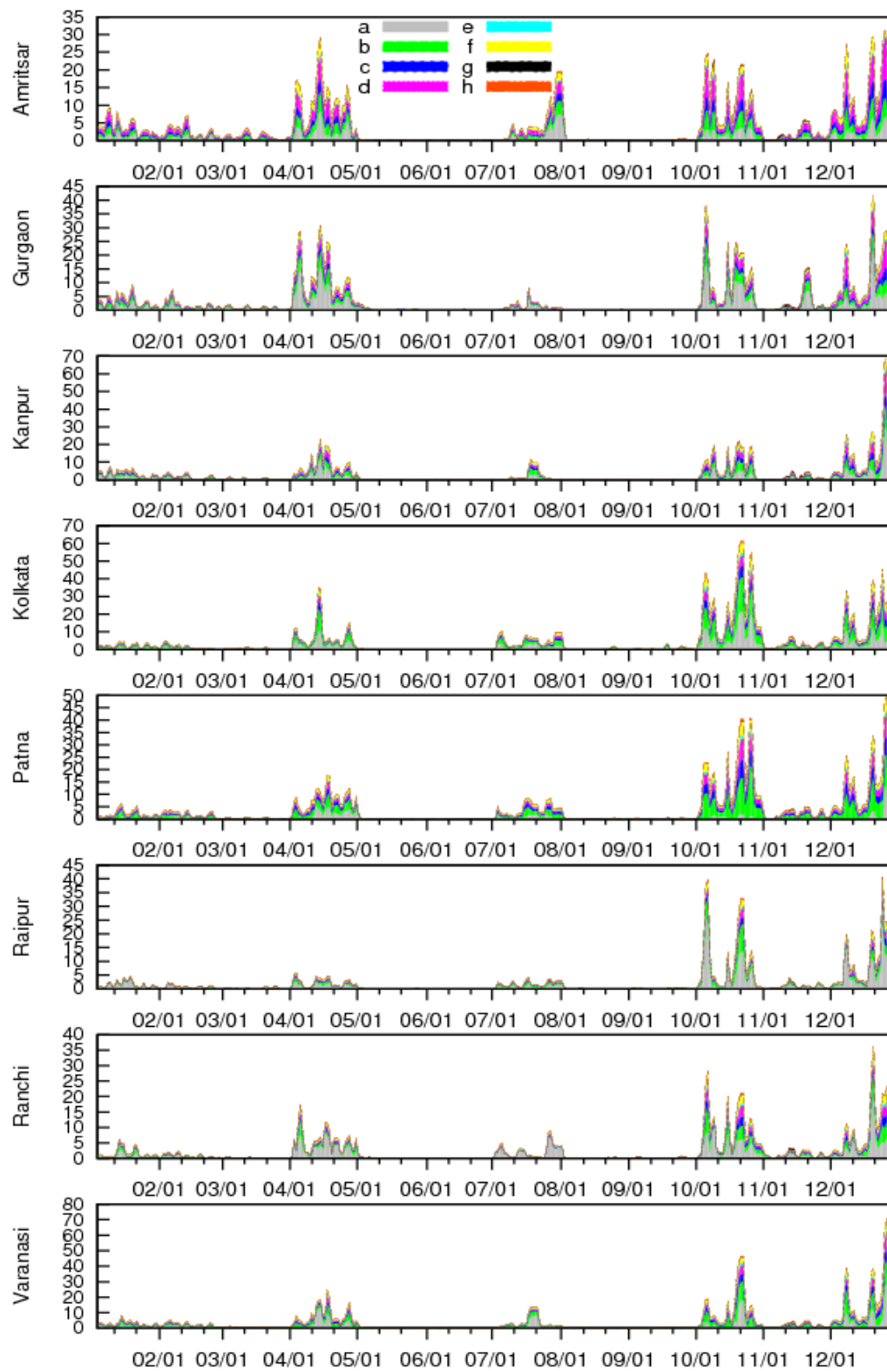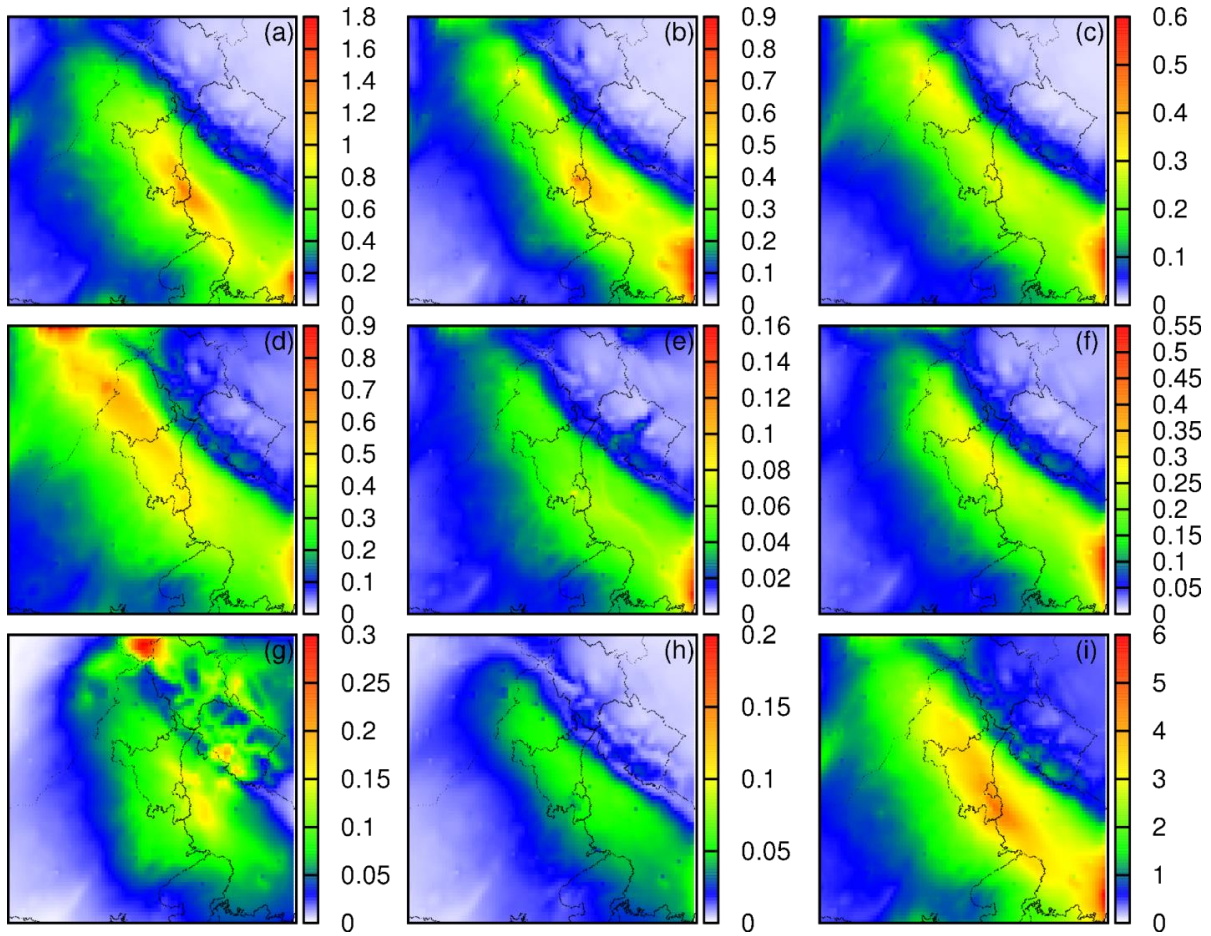
Figure 20. Time series at specific cities in 36 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning and (h) windblown dust. Units are in µg/m³).

Figure 21 of 12 km source apportionment results of nitrate PM demonstrate that high energy nitrate PM concentrations and on-road nitrate PM concentrations in Delhi, Punjab, Haryana and Parts of North Uttar Pradesh should be the major contributors to total nitrate PM at this area.

Figure 21. Source apportionment of NO₃ in 12 km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f)agriculture, (g) open burning, (h) windblown dust and (i) total. Units are in µg/m³)

Similar results are obtained from time series source apportionment results of nitrate PM at the four cities in Figure 22. The energy and on-road dominate the total nitrate PM, but industry, residential and agriculture also contribute to total nitrate PM in selected four cities. The detailed percentages of each source type ratio in Total nitrate PM at four cities are shown in Table 13.
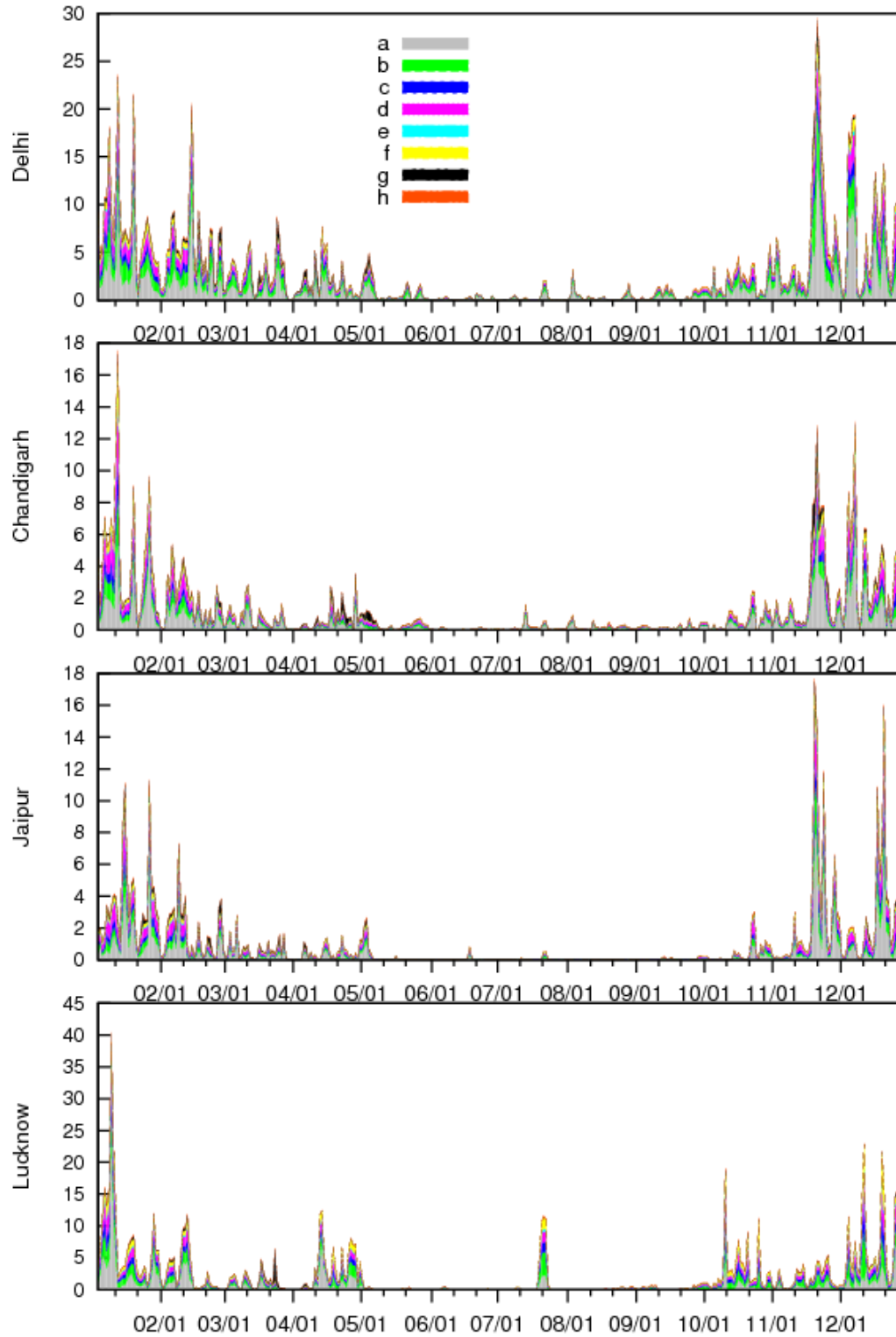
Figure 22. Time series at specific cities (sources type are: (a) energy, (b) industry, (c) residential, (d) onroad, (e) off-road, (f) agr, (g) open burning, and (h) windblown dust. Units are in µg/m³)

Table 13. Contributions of different source sectors to nitrate at selected cities

	energy	industry	residential	On-road	Off-road	agriculture	open burning	Windblown dust
Delhi	38.35%	18.74%	9.81%	18.21%	2.13%	6.67%	2.11%	3.97%
Chandigarh	39.23%	13.10%	10.13%	20.03%	1.96%	9.05%	2.89%	3.60%
Jaipur	34.69%	13.80%	9.74%	22.37%	2.75%	7.71%	4.22%	4.72%
Lucknow	27.43%	21.72%	13.82%	17.40%	3.08%	11.99%	1.75%	2.80%

Source apportionment of nitrate PM simulations based on 9 regions of India were also conducted. Figure 23 shows the regional plot of the regional source apportionment results. East and Northeast India have highest nitrate PM concentrations (up to 3.5 μg/m³).
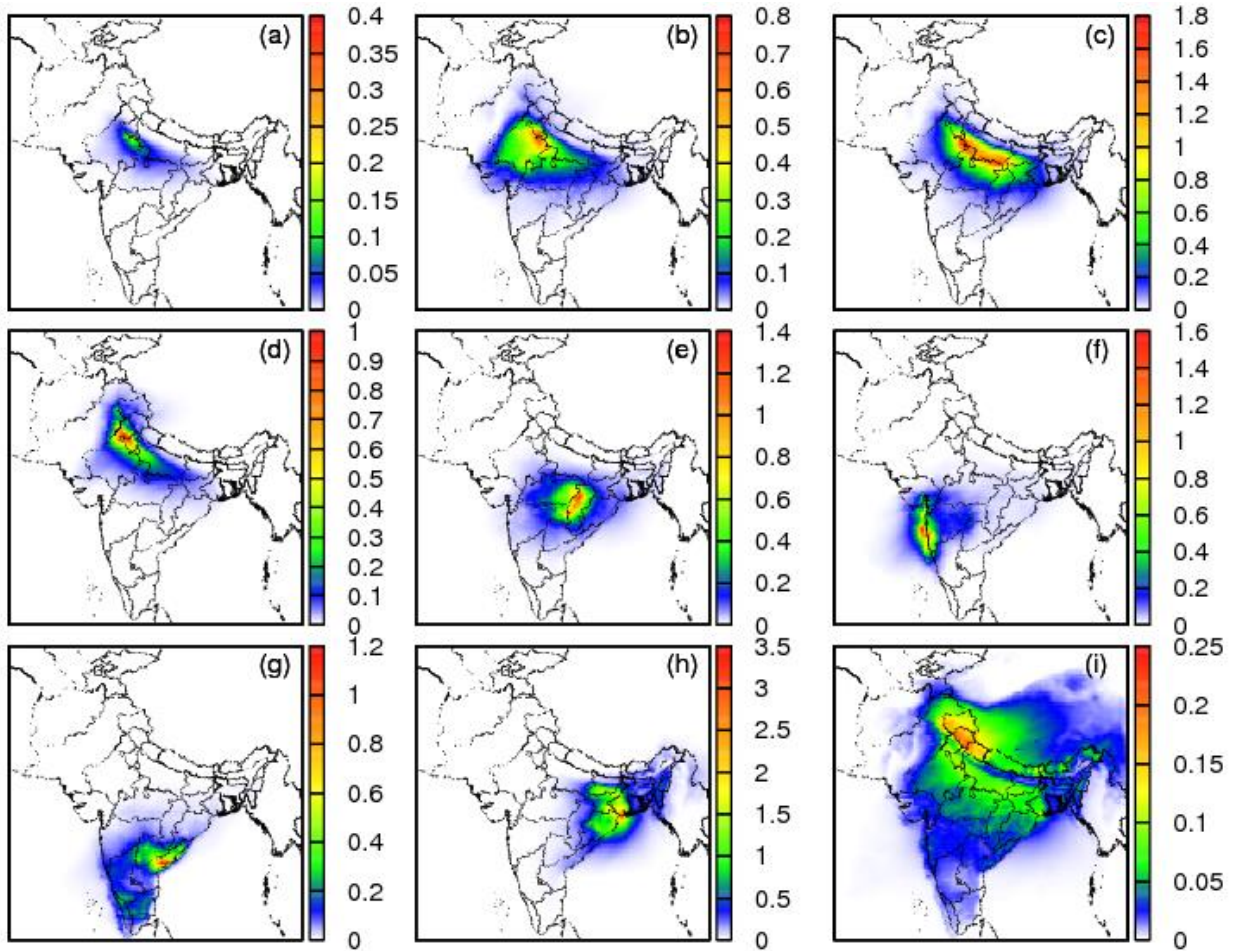

Figure 23. Source apportionment of nitrate PM in 36km domain based on different source regions (source regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, (f) West India, (g) South India, (h) East & Northeast India and (i) Outside India Units are in μg/m³)

Similar to 36 km simulation results, the entire region mainly have a nitrate PM concentration up to 1.2 μg/m³ as in Figure 24.
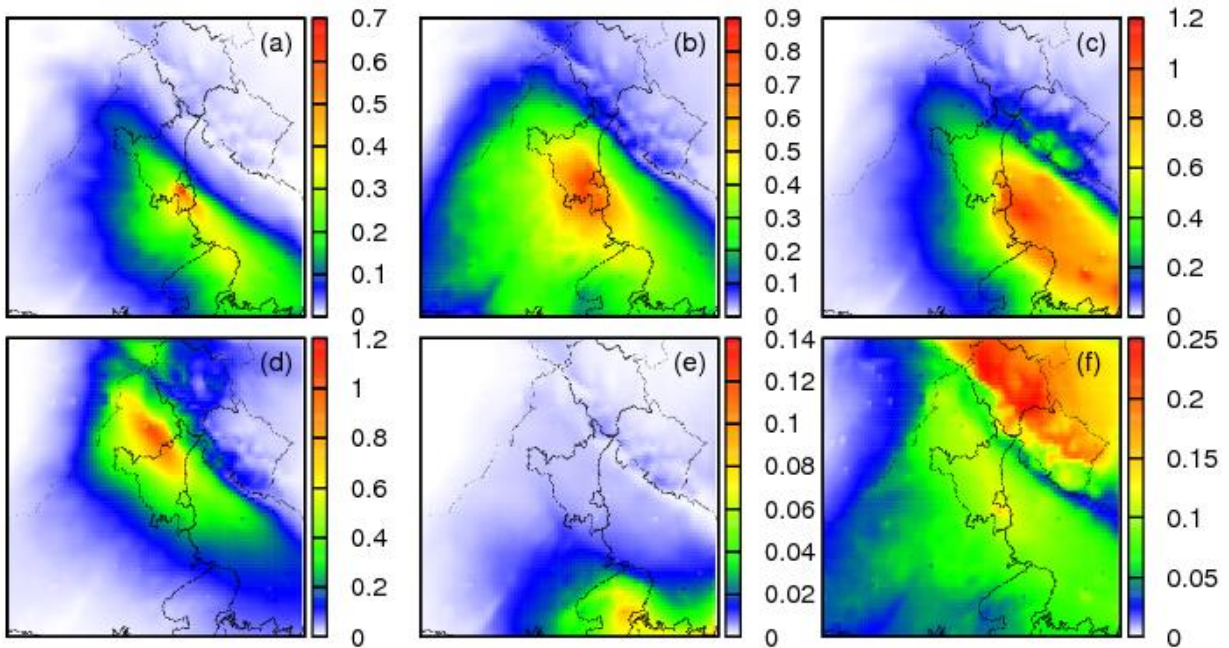

Figure 24. Source apportionment of nitrate PM in 12km domain based on different source regions

As time series plot in Figure 25 and Table 14 shows, unlike from the pervious, the nitrate PM in Delhi comes from 3 sources: within the state, Haryana & Rajasthan and H.Prad,J.kash & Punjab. Each region contributes ~25% to total nitrate PM in Delhi. In other 3 cities, sources within the state dominates total nitrate PM concentrations.
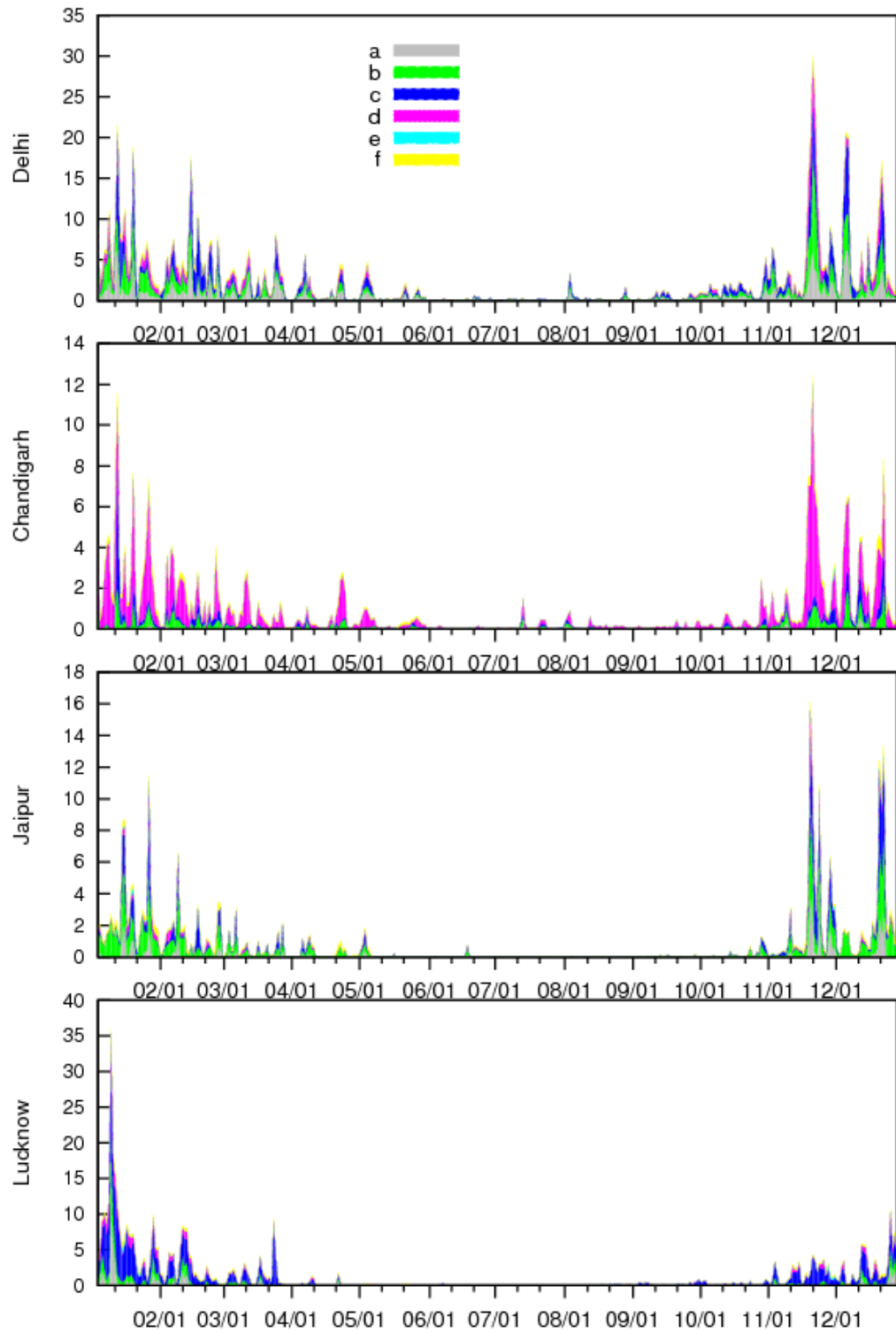
Figure 25. Time series plot at specific cities (sources regions are: (a) Delhi, (b) Haryana and Rajasthan, (c) U.Pradesh and Uttarakhand, (d) H.Prad, J.kash and Punjab, (e) Central India, (f) Outside India)

Table 14. Contributions of different regions to total nitrate PM at selected cities in 12km domain

	Delhi	Haryana and Rajasthan	U. Pradesh and Uttarakhand	H.Prad,J.kash and Punjab	Central India	Outside India
Delhi	24.57%	26.40%	28.75%	14.32%	0.07%	5.88%
Chandigarh	1.99%	16.79%	17.05%	56.60%	0.09%	7.48%
Jaipur	12.77%	49.19%	24.53%	5.04%	1.52%	6.94%
Lucknow	15.68%	18.67%	49.13%	10.88%	0.12%	5.51%

4.4.3 Source apportionment of sulfate

The catalogs are used in analyzing source apportionment of sulfate PM in India as following: energy, industry, residential, on-road, off-road, agriculture, wildfire and background& primary, since the sulfate had primary sources. Figure 26 shows the source apportionment results of sulfate PM in 36km domain. Energy, industry and background & primary sulfate PM are major contributors to total sulfate PM. Energy sulfate PM concentrations are higher in South and Central India and industry sulfate PM concentrations are higher in East India. Figure 27 shows time series plot of source apportionment of sulfate in eight cites (Amritsar, Varanasi, Gurgaon, Kanpur, Patna, Ranchi, Raipur, and Kolkata). Primary sulfate is also broken down to obtain the contributions of sources and regions to total PM$_{2.5}$.
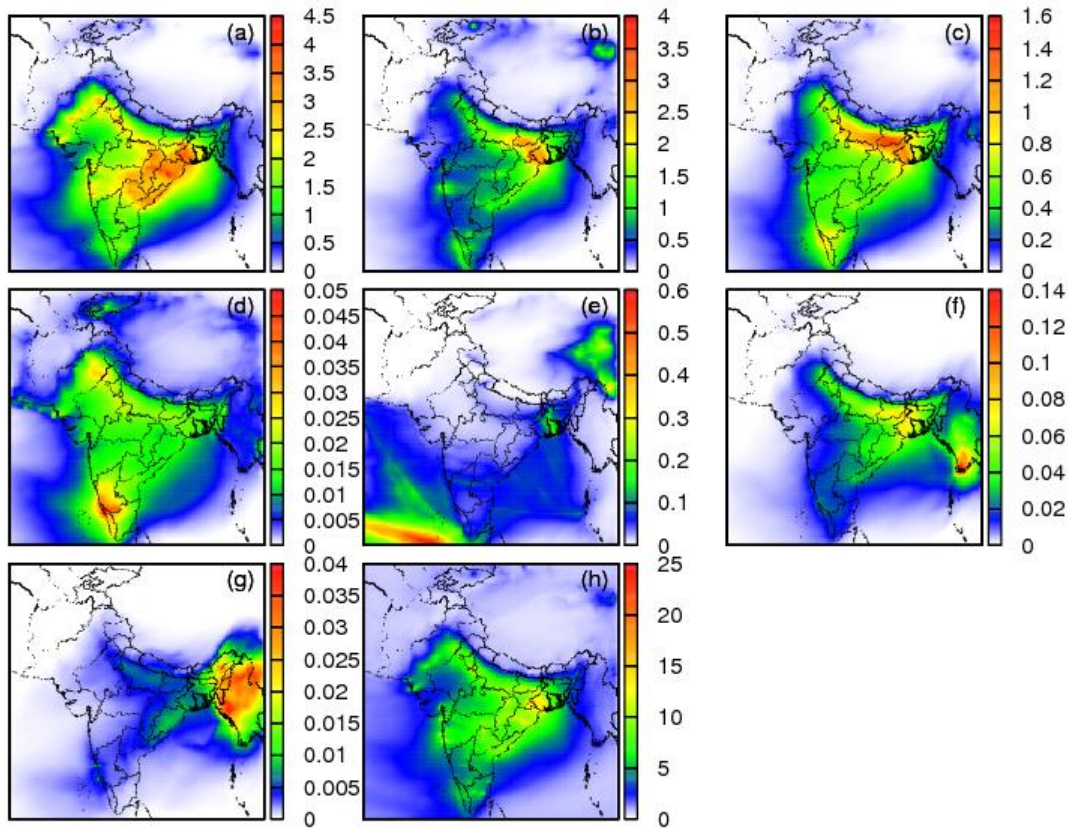

Figure 26. Source apportionment of SO$_4$ in 36 km domain (sources are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) total. Units are µg/m³. As windblown dust does not contribute to sulfate, it is not included).
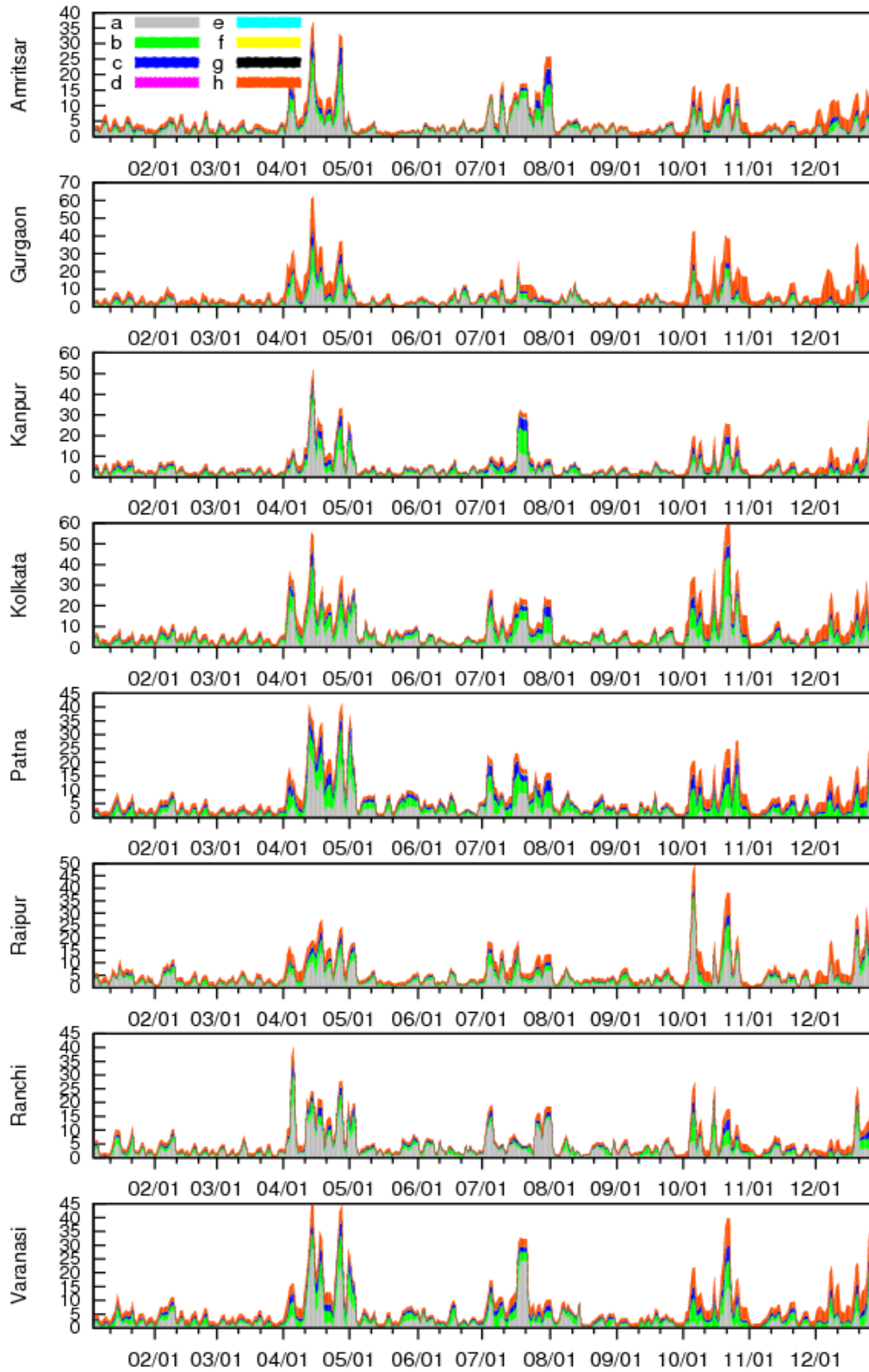
Figure 27. Time series at specific cities in 36km domain (sources type are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) background & primary. Units are in µg/m³)

Similar to 36 km results, Figure 28 of 12 km source apportionment of sulfate PM results shows that high energy sulfate PM concentrations in Delhi, Punjab, Haryana and Parts of North Uttar Pradesh contribute to total sulfate PM and high industry sulfate PM concentrations in North Uttar Pradesh occurs.
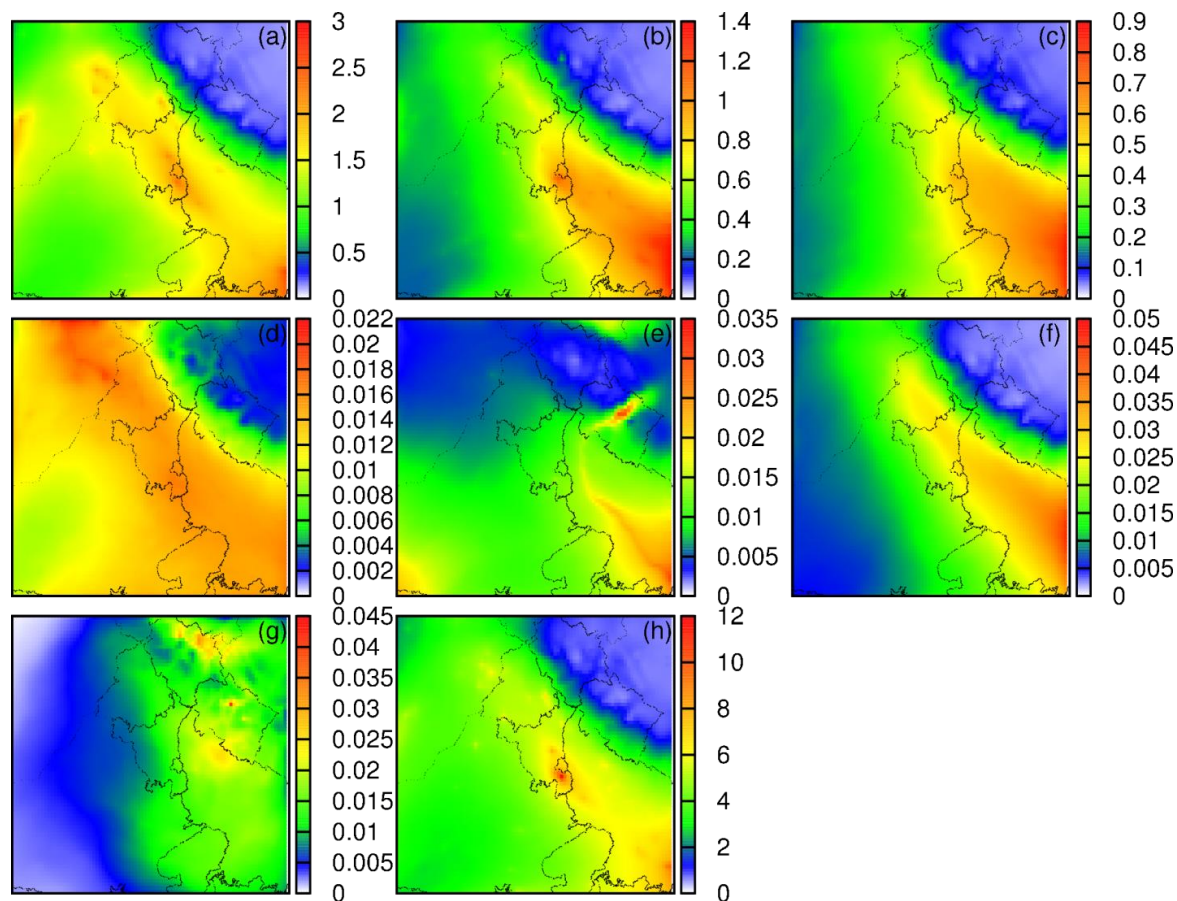

Figure 28. Source apportionment of SO₄ in 12 km domain (sources are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) total. Units are μg/m³. As windblown dust does not contribute to sulfate, it is not included).

Time series plot of selected four cities in Figure 29 shows energy, industry, residential and background are the factors dominate total sulfate concentrations at all four cities especially energy factor. The detailed percentages of each source type ratio in total sulfate PM at four cities are shown in Table 15.
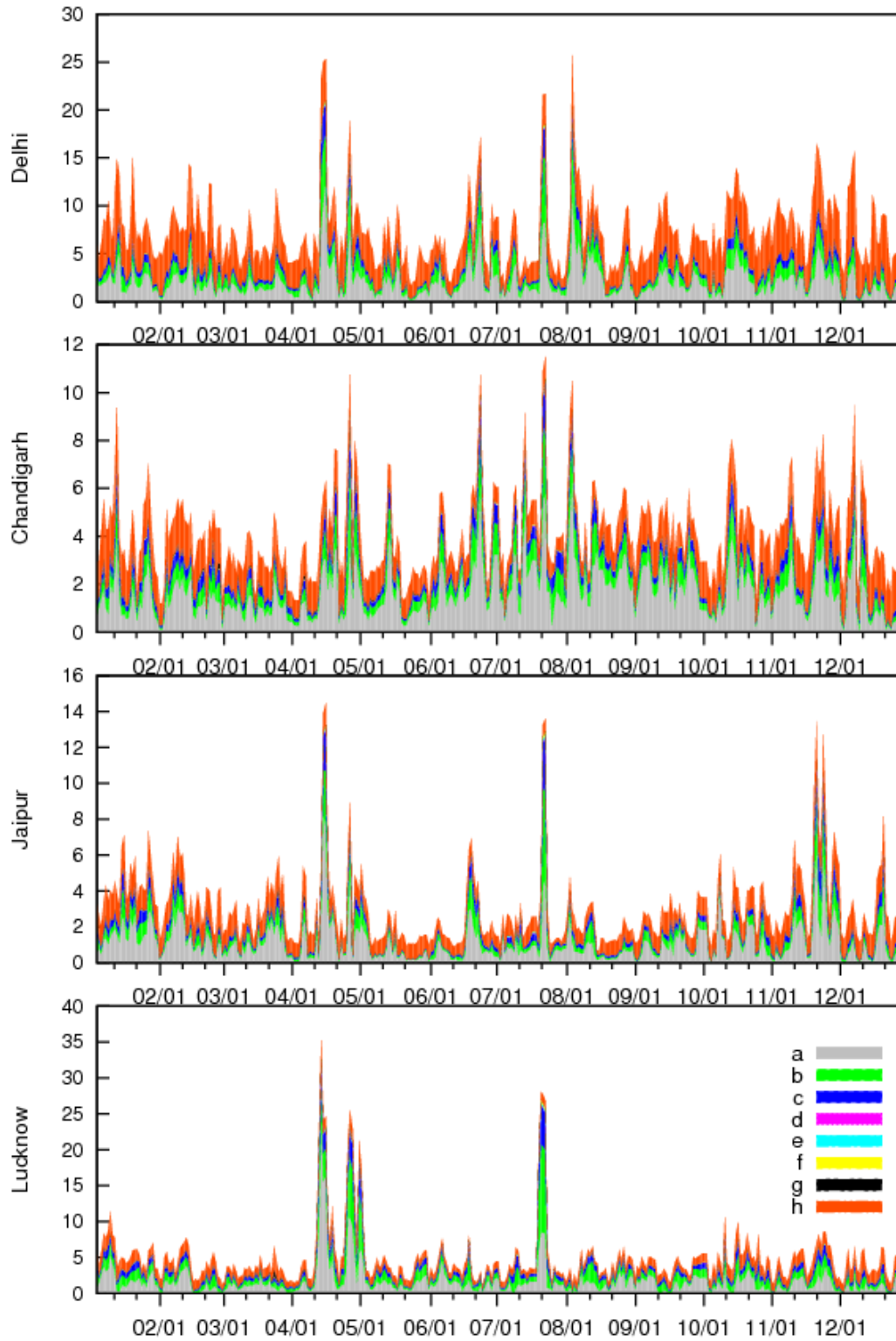
Figure 29. Time series at specific cities (sources are: (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, and (h) primary. Units are in µg/m³)

Table 15. Contributions of different source sectors to sulfate at selected cities.

	energy	industry	residential	onroad	offroad	agriculture	open burning	primary
Delhi	18.53%	8.94%	5.41%	0.16%	0.07%	0.21%	0.06%	66.62%
Chandigarh	33.08%	14.47%	11.24%	0.30%	0.19%	0.54%	0.20%	39.98%
Jaipur	29.63%	14.43%	11.59%	0.39%	0.09%	0.34%	0.20%	43.33%
Lucknow	25.24%	19.75%	13.91%	0.27%	0.27%	0.61%	0.13%	39.83%

Source apportionment of sulfate PM simulations based on 9 regions of India were also conducted. Figure 30 shows the regional plot of the regional source apportionment results. East and Northeast India have highest sulfate PM concentrations (up to 4 μg/m^3).
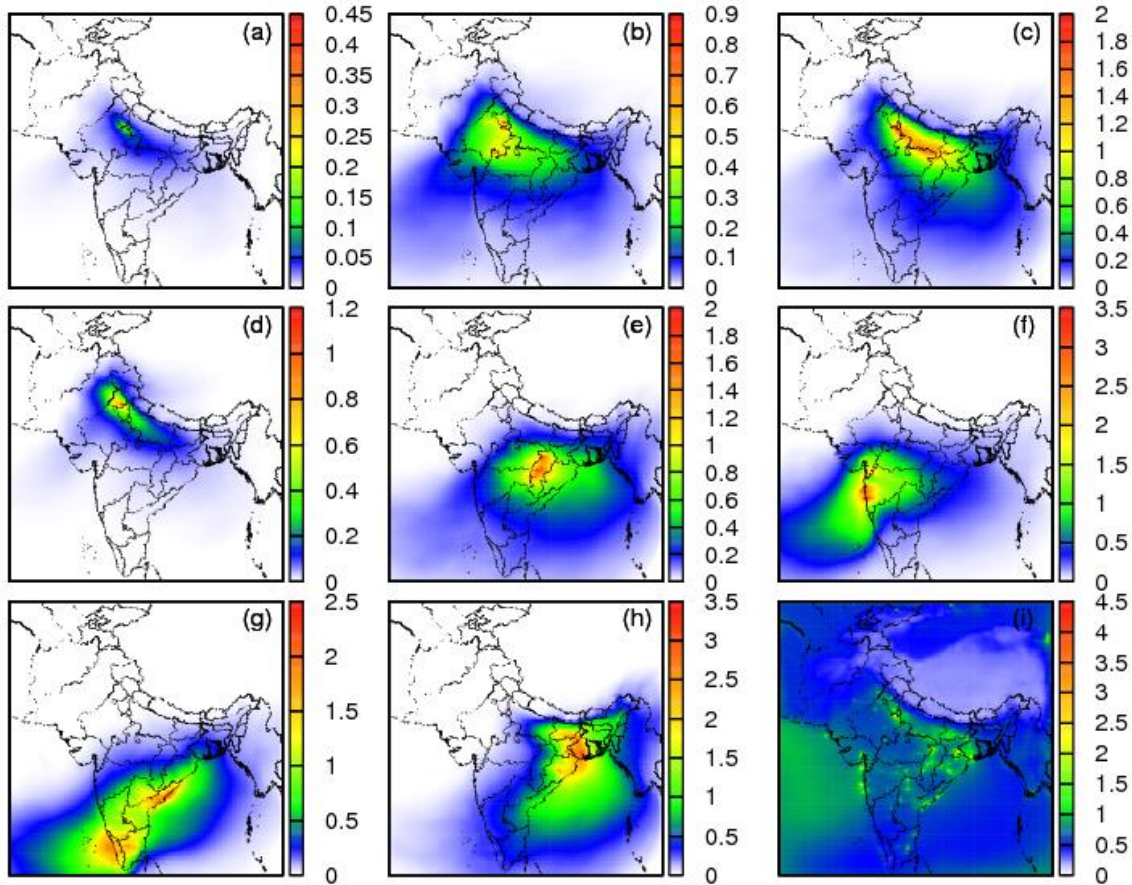

Figure 30. Source apportionment of sulfate PM in 36km domain based on different source regions (regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, (f) West India, (g) South India, (h) East & Northeast India and (i) primary. Units are μg/m^3)

In 12 km domain simulation as shown in Figure 31, the primary sources of sulfate PM dominates entire region. Also, U.Pradesh and Uttarakhand have a high secondary sulfate PM concentration up to 1.6 µg/m^3.
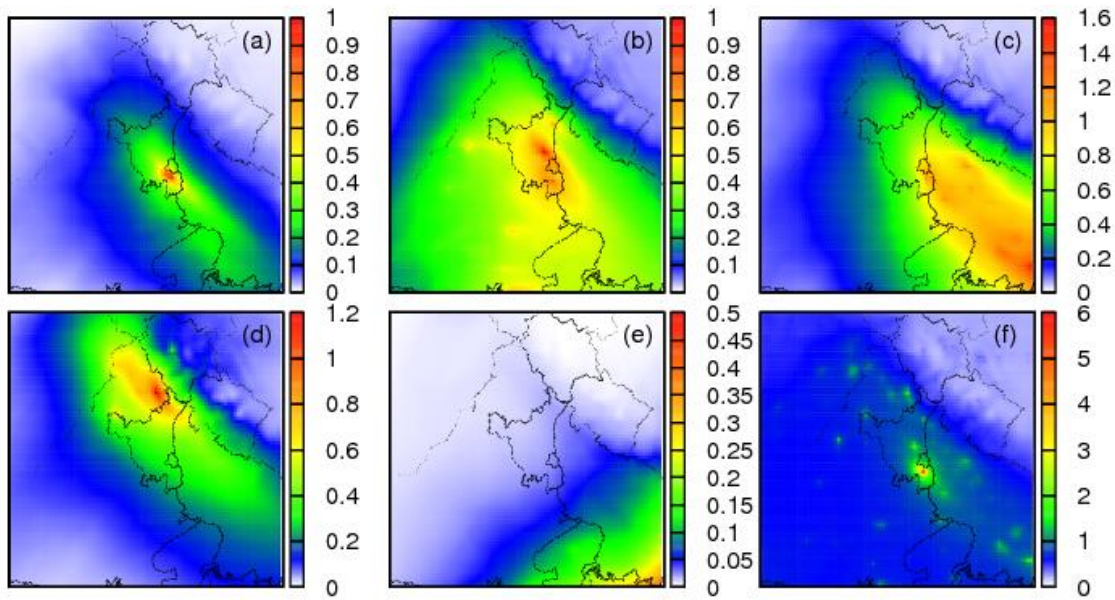

Figure 31. Source apportionment of sulfate PM in 12km domain based on different source regions (regions are: (a) Delhi, (b) Haryana & Rajasthan, (c) U.Pradesh & Uttarkhand, (d) H.Prad & Punjab, (e) Central India, and (f) primary. Units are µg/m^3)

As time series plot in Figure 32 and Table 16 shows, the sulfate PM in 4 cities mainly comes from primary sources (~40%, 70% in Delhi). However, the secondary sulfates PMs are more likely from within the states in Lucknow and Jaipur.
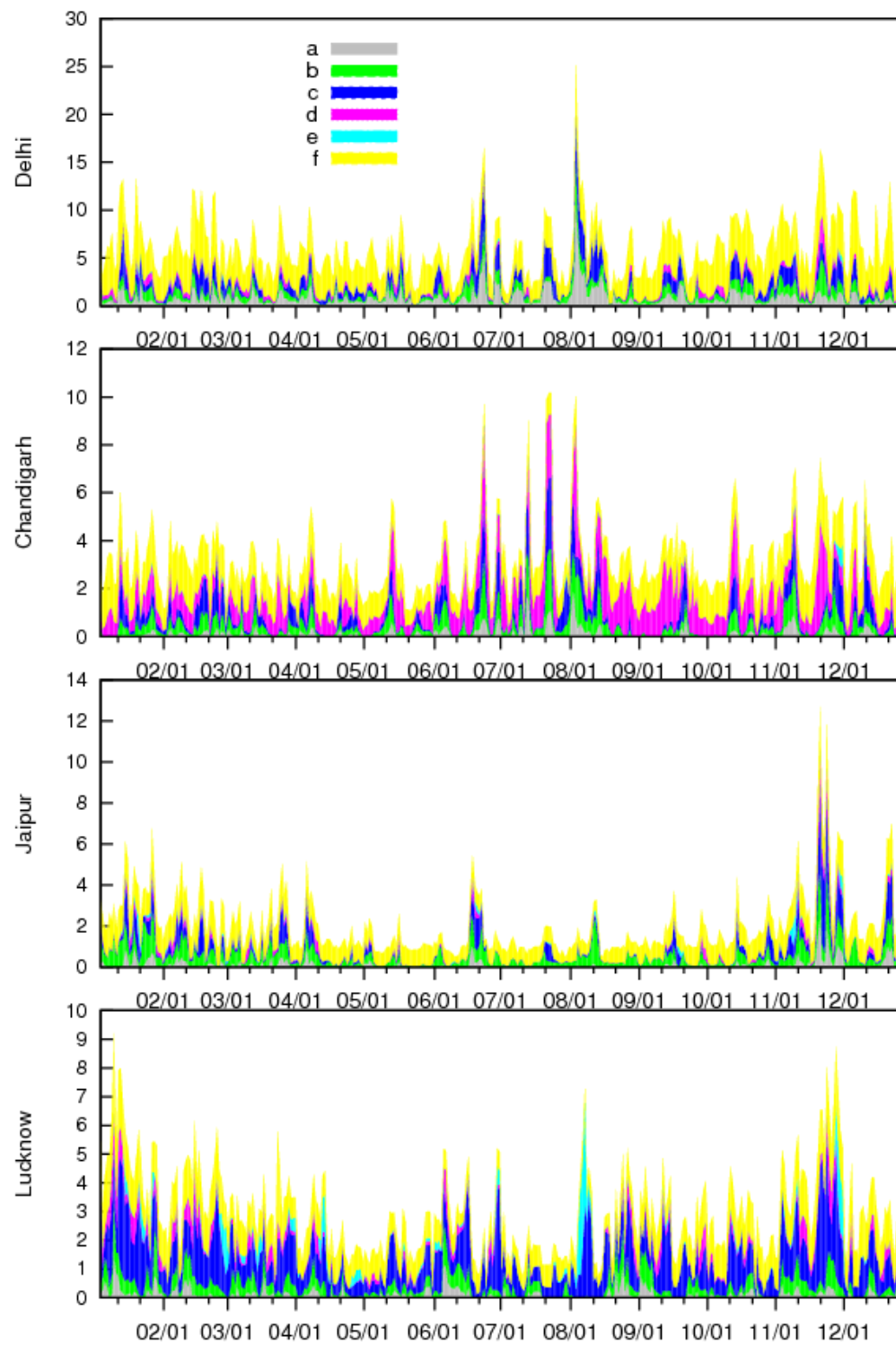
Figure 32. Time series plot at specific cities (sources regions are: (a) Delhi, (b) Haryana and Rajasthan, (c) U.Pradesh and Uttarakhand, (d) H.Prad, J.kash and Punjab, (e) Central India, (f) Primary)

Table 16. Contributions of different regions to total sulfate PM at selected cities in 12km domain.

	Delhi	Haryana and Rajasthan	U.Pradesh and Uttarakhand	H.Prad,J.kash and Punjab	Central India	Primary
Delhi	7.83%	6.99%	9.07%	4.60%	0.10%	71.41%
Chandigarh	3.78%	11.11%	18.58%	20.65%	0.29%	45.58%
Jaipur	6.60%	26.77%	15.39%	4.97%	1.00%	45.28%
Lucknow	6.19%	10.18%	31.57%	8.41%	0.54%	43.10%

4.5 Source apportionment of total PM$_{2.5}$

Instead of study PPM, ammonia, nitrate and sulfate separately, we analyzed contribution of each source type to total PM by adding up the source apportionment results of each components of PM. In Figure 33, industry, residential and agriculture contribute to major PM concentrations at extreme polluted region from North India to East India and energy contributes most to Central India. Windblown dust makes a high contribution to total PM in some areas outside India like Tibet and Iran.

Figure 33. Relative source contribution in 36 km domain of different source types (a) energy, (b) industry, (c) residential, (d) on-road, (e) off-road, (f) agriculture, (g) open burning, (h) windblown dust and SOA concentrations (i). Units are µg/m³.

In Figure 34, the 12km results show energy, industry and residential are the three major contributors to Total PM. The energy and industry PM concentrations are high at South Delhi and its surroundings. Also, the residential PM concentrations remain a high level at Delhi, Punjab, Haryana and Parts of North Uttar Pradesh in Table 17.
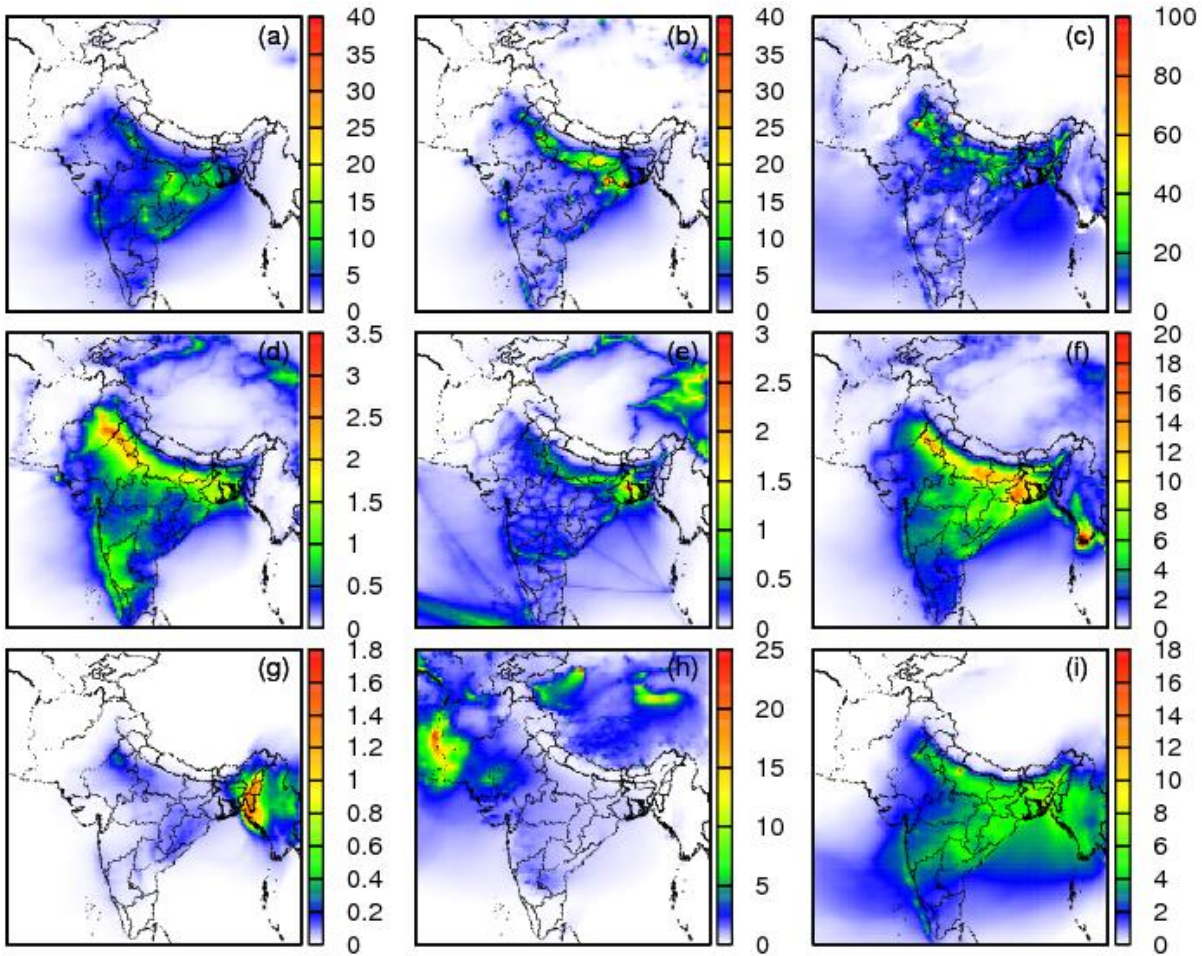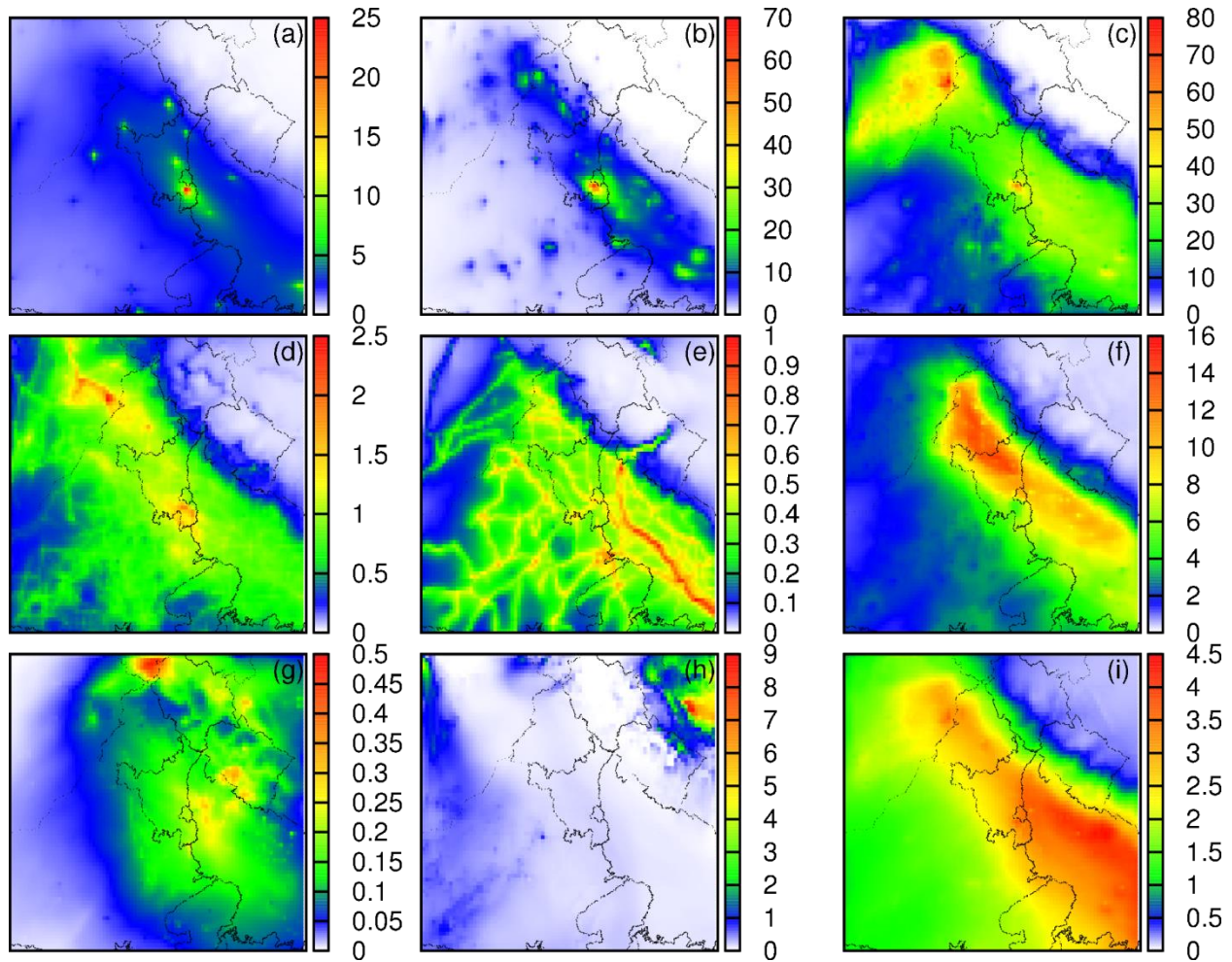

Figure 34. Relative source contributions in 36 km domain of different source types (a) energy, (b) industry, (c) residential, (d) onroad, (e) off-road, (f) agr, (g) open burning, (h) windblown dust and SOA concentrations (i). Units are µg/m³

Table 17. Contributions of different source sectors to total PM$_{2.5}$ at selected cities.

	energy	industry	residential	onroad	offroad	agriculture	open burning	Windblown dust	SOA
Delhi	15.71%	33.37%	37.91%	1.26%	0.31%	6.49%	0.05%	2.13%	2.77%
Chandigarh	11.49%	28.43%	39.21%	4.36%	0.39%	9.97%	0.19%	1.60%	4.36%
Jaipur	14.22%	29.70%	33.97%	3.82%	1.12%	7.09%	0.34%	2.65%	7.09%
Lucknow	12.07%	32.05%	30.53%	8.04%	0.36%	10.47%	0.12%	1.80%	4.56%

4.6 Health effects

4.6.1 Regional and state premature mortality in India

Figure 35 shows the predicted annual $PM_{2.5}$ concentrations in India for 2015, with maximum of > 120 µg m^{-3} in Delhi and some states at East India. The premature mortality linked to COPD, LC, IHD and CEV for adult ≥ 25 years old was calculated, as shown in Figures 35. The total premature morality due to these four diseases was shown in Figure 35. In major urban areas where population density is high, the total mortality can be much greater than 3000 cases per year per grid cell (i.e., 36 km×36 km). High premature mortality occurs in the Indo-Gangetic plains and East India. The estimated national $PM_{2.5}$ related premature mortality for adults ≥ 25 years old in 2013 is approximately 1.04 million with CI95 of 0.53-1.54 million.
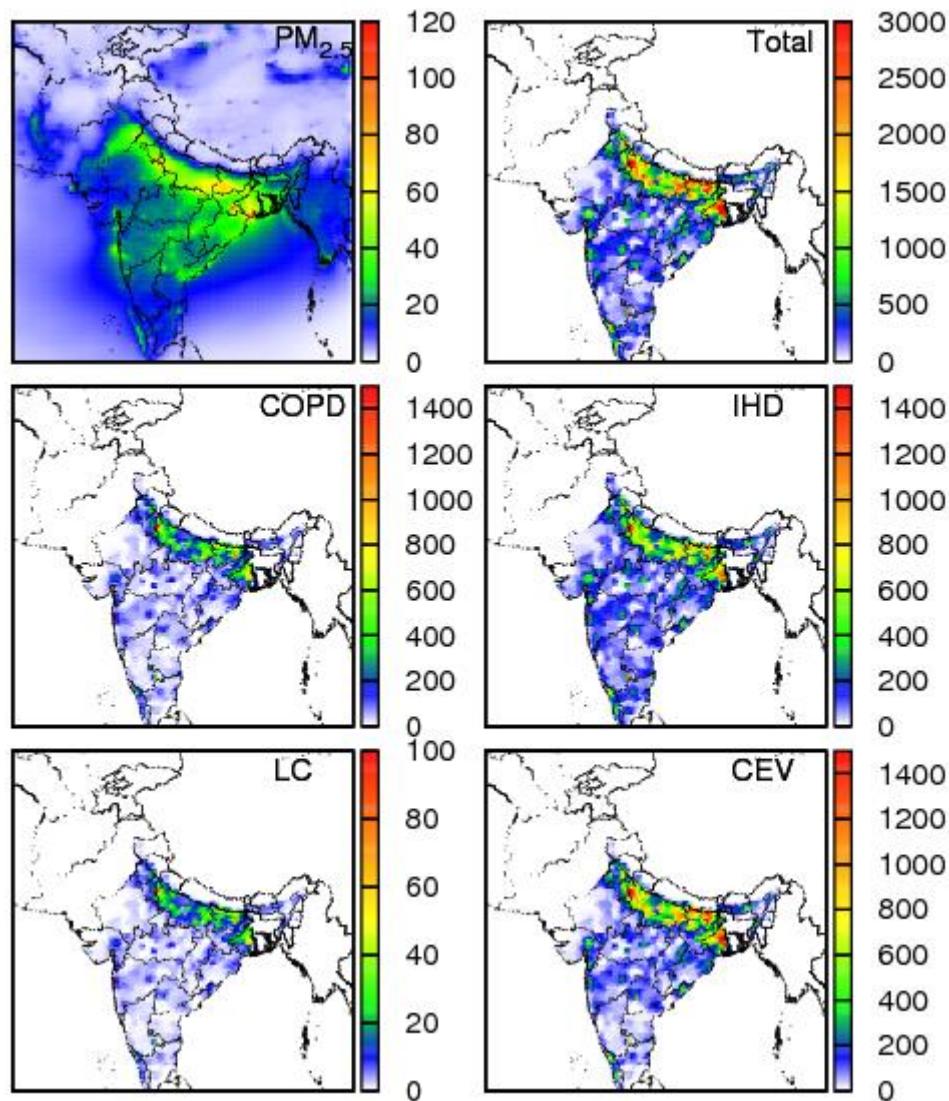

Figure 35. Predicted annual $PM_{2.5}$ concentrations (µg m-3), total premature mortality (death per area of 36 km × 36 km) and premature mortality due to COPD, LC, IHD and CEV in India.
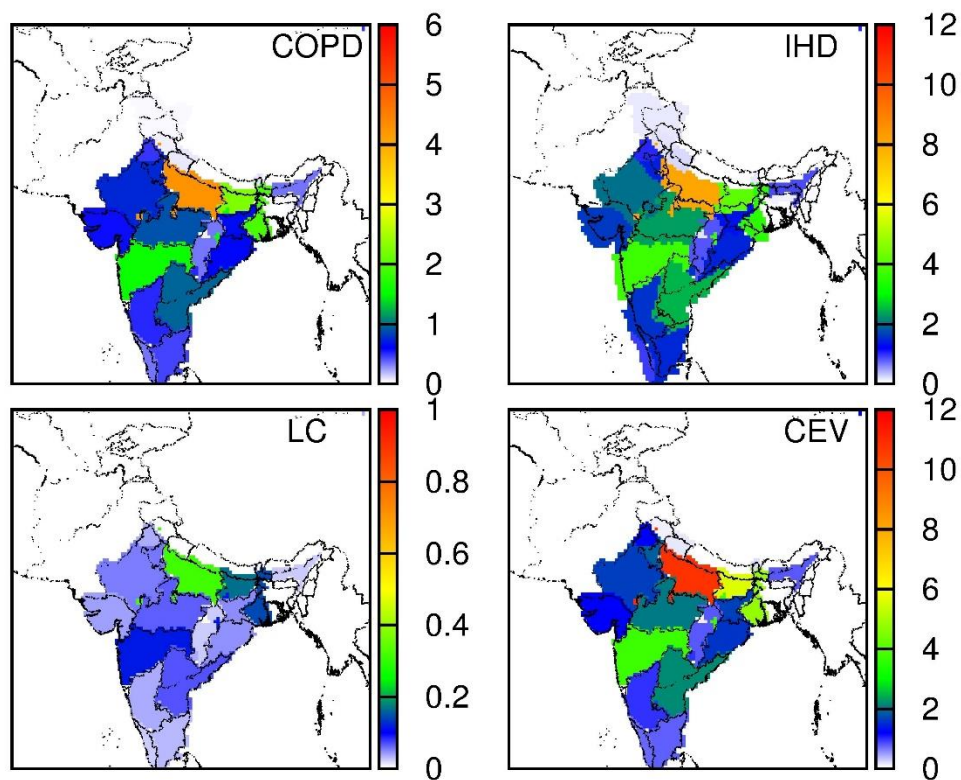
Figure 36. State excess disease specific mortality (x10⁴ deaths) in 2015 due to COPD, LC, IHD and CEV for age >= 25 years in 2015 due to high PM₂.₅ concentrations.

4.6.2 Source apportionment of premature mortality in India

Figure 37 shows the total premature mortality due the eight source types. Residential followed by Industry, Agriculture, Energy were the major sources contributing to premature mortality due to $PM_{2.5}$ concentration. Majority of premature mortality in all the states apart from the ones which didn't had any source information were observed to be contributed by residential sources (above 1500). This is indicative of the fact that majority of households in India use solid fuels for cooking instead of gas and electricity. Delhi was found to be affected the most among all states by industrial sources while mortality due to emission from Energy generation was found to be the highest in mineral rich state of Chhattisgarh. Agricultural emissions contributed the most towards premature mortality in Arunachal Pradesh. Agricultural emissions were also found to contribute significantly to premature mortality in other northeastern states. Detailed contribution of different sources to total premature deaths for both the whole country and each state were listed in Table 18.
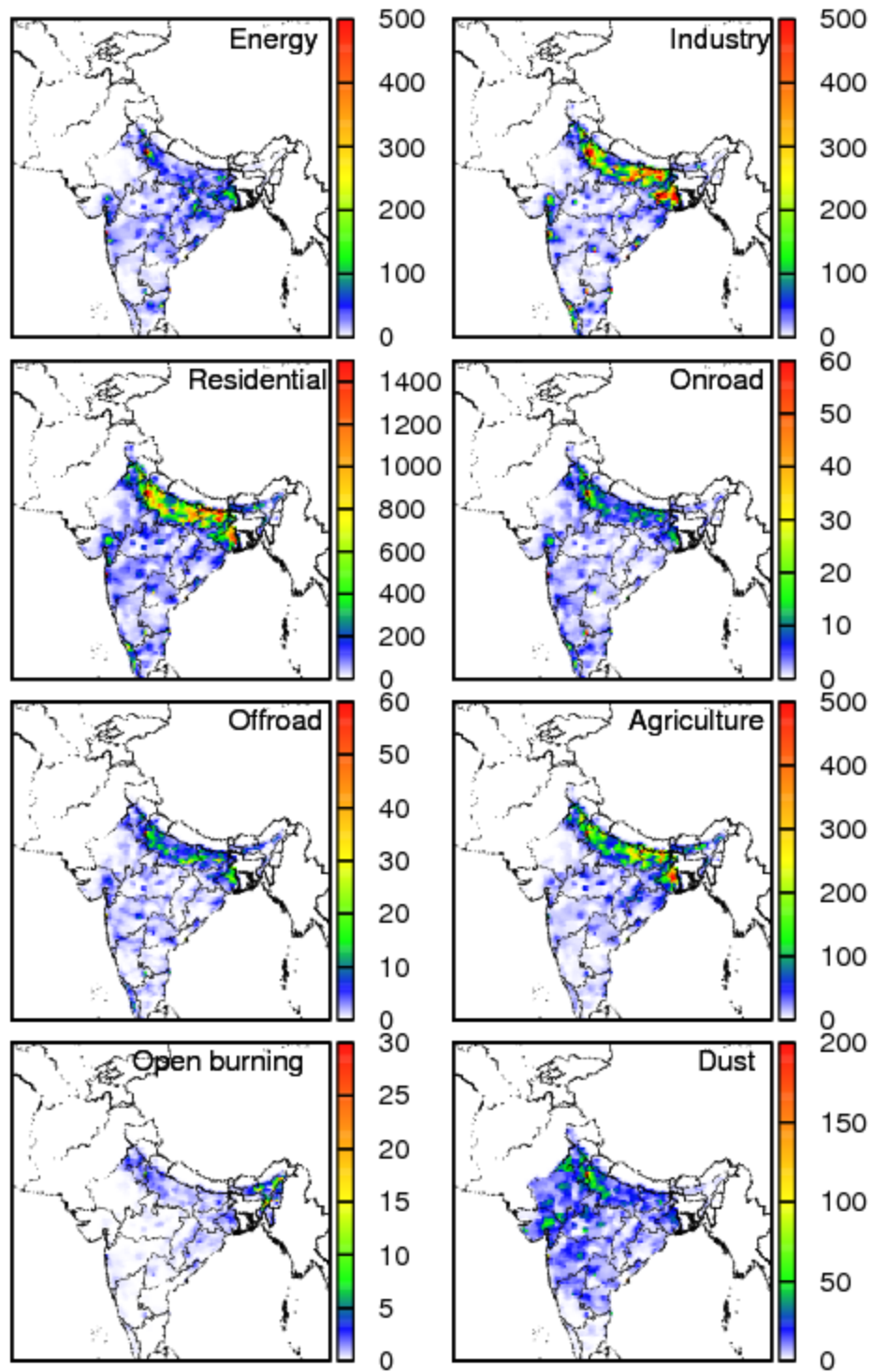
Figure 37. Source apportionment of total premature mortality (deaths per area of 36 km × 36 km) in India, 2015.

Table 18. Source contribution to premature mortality due to COPD, LC, IHD and CEV for ages larger than 25 years.

State		Energy	Industry	Residential	On-road	Off-road	Agriculture	Open-burning	Windblown dust
Andhra Pradesh	AN	13.5%	18.75%	48.5%	1.25%	1.25%	9.75%	0.25%	6.75%
Assam	AS	1.875%	6.875%	61.25%	0.625%	1.25%	24.37%	2.5%	1.25%
Bihar	BR	2.32%	18.70%	62.01%	0.66%	0.66%	13.96%	0.08%	1.24%
Chhattisgarh	CT	22.625	13.13%	40.87%	0.73%	0.73%	0.73%	16.78%	5.1%
Goa	GO	14.28%	14.28%	57.14%	0%	0%	14.28%	0%	0%
Gujrat	GJ	10.23%	17.40%	53.24%	1.70%	1.02%	5.11%	0%	11.26%
Haryana	HR	6.42%	25.71%	52.14%	1.42%	0.71%	9.28%	0.238%	4.28%
Himachal Pradesh	HP	9.67%	12.90%	54.83%	3.22%	0%	12.90%	0%	6.45%
Jammu &Kashmir	J&K	0%	9.09%	68.18%	0%	0%	13.63%	0%	9.09%
Jharkhand	JK	10.06%	26.29%	48.05%	0.649%	0.97%	12.01%	0.32%	2.27%
Karnataka	KT	9.40%	14.35%	54.95%	3.46%	1.48%	8.91%	0.49%	6.93%
Kerala	KR	3.41%	26.13%	62.5%	1.70%	1.13%	3.40%	0%	0.56%
Lakshadweep	LW	0%	0%	0%	0%	0%	0%	0%	0%
Madhya Pradesh	MP	10.85%	10.59%	55.29%	1.03%	1.03%	12.14%	0.258%	9.04%
Maharashtra	MH	11.44%	23.87%	49.01%	1.13%	0.98%	7.76%	0.14%	5.64%
Meghalaya	MG	5.55%	11.11%	55.55%	0%	0%	22.22%	0%	0%
Nagaland	NL	0%	12.5%	62.5%	0%	0%	12.5%	12.5%	0%
Delhi	DL	5.83%	40%	45.83%	0.83%	0.83%	4.16%	0%	2.5%
Odisha	OS	17.39%	14.62%	45.45%	0.79%	0.79%	17%	0.39%	3.95%
Puducherry	PD	12.5%	25%	50%	0%	0%	12.5%	0%	0%
Punjab	PN	3.75%	14.28%	57.51%	1.50%	0.75%	17.67%	0.375%	4.51%
Rajasthan	RA	4.88%	9.19%	57.47%	2.011%	1.14%	7.75%	0.28%	17.24%
Sikkim	SK	7.40%	38.88%	46.29%	1.85%	0%	3.70%	0%	1.85%
Tamil Nadu	TN	15.11%	19.55%	52.88%	1.77%	0.88%	7.55%	0%	1.77%
Tripura	TP	5.26%	5.26%	63.15%	0%	0%	21.05%	0%	0%
Uttar Pradesh	UP	4.03%	18.75%	61%	0.83%	0.83%	12%	0.08%	2.45%
Uttarakhand	UK	2.63%	10.52%	65.78%	2.63%	2.63%	13.15%	0%	5.26%
West Bengal	WB	5.21%	26.68%	49.54%	0.60%	0.70%	15.84%	0.1%	1.30%
India	IN	6.799%	19.66%	55.45%	1.05%	0.85%	11.90%	0.23%	4.02%

4.7 Future emission scenarios

In base case shown in Figure 40, $PM_{2.5}$ concentration varied in different seasons. High concentration occurred in winter in regions 1, 2, 3, 4, and 8 as region numbers in **Figure 2**, while the rest of India was in concentration from around 20 to 60 μg/m^3. In April and July, most India was in low $PM_{2.5}$ concentrations. However, regions 1, 2, 3, 4, and 8 remains in higher concentrations than other regions. The health effects for different emission scenarios were shown in Figure 41.

Implementing new emissions standards in operating power plants (S1) reduced $PM_{2.5}$ average annual concentrations significantly on the national level, particularly in central and northwestern India and particularly during the winter, avoiding 110,000 premature deaths per year. Concentrations fell slightly in April and October in areas with the highest concentration levels.

Especially, concentration in southern and eastern coastal region decreased significantly in October. In December, $PM_{2.5}$ fell greatly in areas with high pollutant concentrations in Delhi and across the Indo-Gangetic plain from Punjab to Uttar Pradesh and in the northeast (regions 1, 2, 3, 4, and 8). However, $PM_{2.5}$ concentrations slightly increased in central India and the northeast in July. Analysis of the impacts of under-construction power plants not following new emission standards (S2) indicated that these emissions from new plants would increase pollution levels on the national level, leading to 14,000 premature deaths, but with a varied regional impact. In April, July, and October, concentrations in regions 1, 2, 4 are slightly reduced while there are promotions occurred in the most of rest regions. A significant increase was found in north region 7 in October. A great decrease occurred in Delhi, Haryana & Rajasthan and Punjab & Himachal Pradesh in December and a significant increase also been found in northern part of South India. Increased emissions from new planned thermal power plants (S3) would lead to increased $PM_{2.5}$ concentrations, with the exception of Delhi, Haryana and Punjab, causing an estimated 26,000 premature deaths per year. Significant increases were found in Central, West, South and East and Northeast India in April, October, and December. In total, 151,000 premature deaths per year could be avoided through the three measures targeting the power sector.

Reducing solid fuel use in households (S4) reduced $PM_{2.5}$ concentrations significantly especially in the region between Punjab and Uttar Pradesh, and in the Northeast, avoiding 258,000 premature deaths per year. Concentrations reduced greatly in October and December compared to the variations in April and July. Reducing crop-burning (S5) caused slight variations in $PM_{2.5}$ concentrations in April, July and October, and there were decreases in Delhi, Uttar Pradesh, Uttarakhand and the Northeast. Besides, $PM_{2.5}$ concentrations slightly increased in the ocean surface west of the West Indian region. In December, $PM_{2.5}$ concentrations in whole terrestrial India decreased, with significant reductions found in the northeast. In total, an estimated 55,000 premature deaths per year could be avoided through this measure. The main burning seasons, May and November, were not included; their inclusion would increase the estimated impact.

Reducing municipal solid waste burning (S6) decreased $PM_{2.5}$ concentrations in December compared to base case especially in the Central and Northeastern regions. However, concentrations in April, July, and October showed no change except for very slight decreases in coastal areas of Southern India in April and October. Overall, 46,000 premature deaths per year could be avoided through this measure. In the scenario assessing the application of stricter Bharat standards (S7), $PM_{2.5}$ concentrations in India remain unchanged or only very slight decreased in April and July but show increased events in October in most part in India except for Haryana & Rajasthan and Himachal Pradesh & Punjab. However, $PM_{2.5}$ concentrations reductions occurred in December especially in the Central and Northeastern regions, leading to 47,000 avoided premature deaths per year. Slower oil consumption growth (S8) would see $PM_{2.5}$ concentrations remain unchanged or only very slightly decreased in April and July. In October, concentration reductions were significantly observed in whole India. Reductions in December were similar to those in scenario 7, and avoided premature deaths amounted to 33,000 per year.

Shifting to zig-zag kilns in brickmaking (S9) would reduce $PM_{2.5}$ concentrations slightly in April, July, and October in Uttar Pradesh & Uttarkhand, Himachal Pradesh & Punjab and the

northwestern part of the east-northeast region. In October, the Central and the southern part of the Northeast region also saw reductions in PM$_{2.5}$ concentrations. In December, concentration reduction was significant and the variation were increased in Uttar Pradesh & Uttarkhand and the Northeast, with the potential to avoid a total of 83,000 premature deaths per year. Shifting to stronger oil sulfur limits (S10) saw PM$_{2.5}$ concentrations decreased very slightly in April in north India. Similar situation occurred in October. In July, reduction was slightly larger in Uttar Pradesh & Uttarkhand, Himachal Pradesh & Punjab, and the Northeast. The reduction was significantly larger in December, especially in Uttar Pradesh & Uttarkhand, Central India and the Northeast, with the projected health benefits amounting to 53,000 avoided premature deaths. Significant concentration reductions were observed in the scenario of introducing strong industrial emissions standards (S11). Though in April and July, only Uttar Pradesh & Uttarkhand and northern part of the Northeast region showed significant decreased in PM$_{2.5}$ concentrations, the reduction increased in October in quantity and in geographical range. Great decrease occurred in Uttar Pradesh & Uttarkhand, Central India and the Northeast in October and the reduction increased further in December as well in same regions. Approximately 184,000 premature deaths could be avoided through these standards.

Controlling construction dust emissions (S12) left PM$_{2.5}$ concentrations unchanged in April and October, and only slightly decreased concentrations in the middle part of the Northeast region in July, leaving the rest region with unchanged concentrations. However, a significant decrease was observed in December in almost entire India. Projected amount of premature deaths avoided was 42,000. Reducing diesel generating sets use (S13) induced large changes in PM$_{2.5}$ concentrations in Uttar Pradesh & Uttarkhand, Himachal Pradesh & Punjab, and the Northeast in October and December; in the rest of India the reduction was relatively smaller but also significant. In April and July, concentration reductions that occurred in Uttar Pradesh & Uttarkhand, Himachal Pradesh & Punjab, and the Northeast were significant while the concentrations remained unchanged or decreased only slightly in West and South India. In total all scenarios put together projected 858,900 premature deaths can be avoided through these measures.

In Table 19, national population averaged concentrations of PM$_{2.5}$ in India under 13 emission scenarios were estimated. Except for power sector scenarios 2 & 3 , which assessed the impacts of increased emissions from new thermal power plants, all the scenarios had a positive effect on reducing PM$_{2.5}$. S5, S6, S7, S8, S9, S10 and S12 slightly reduced potential PM$_{2.5}$ concentration by ~ 1 μg/m^3 and applying new emission standards in industry (S11) had largest effect on reducing PM$_{2.5}$ for 2.95 μg/m^3. The corresponding premature mortality deductions of all scenarios were shown in Table 20. Similar with PM$_{2.5}$ prediction results, all the scenarios had a positive effect on reducing premature mortality. Applying new emission standards in industry (S11) had largest effect on reducing premature mortality for 184,000 deaths per year, followed by reduce household solid fuels reduced 176,900 deaths. If all the measures are combined, it could reduce the population averaged PM$_{2.5}$ levels by 40% nationwide, leading to a total of 858,900 avoided premature deaths per year.
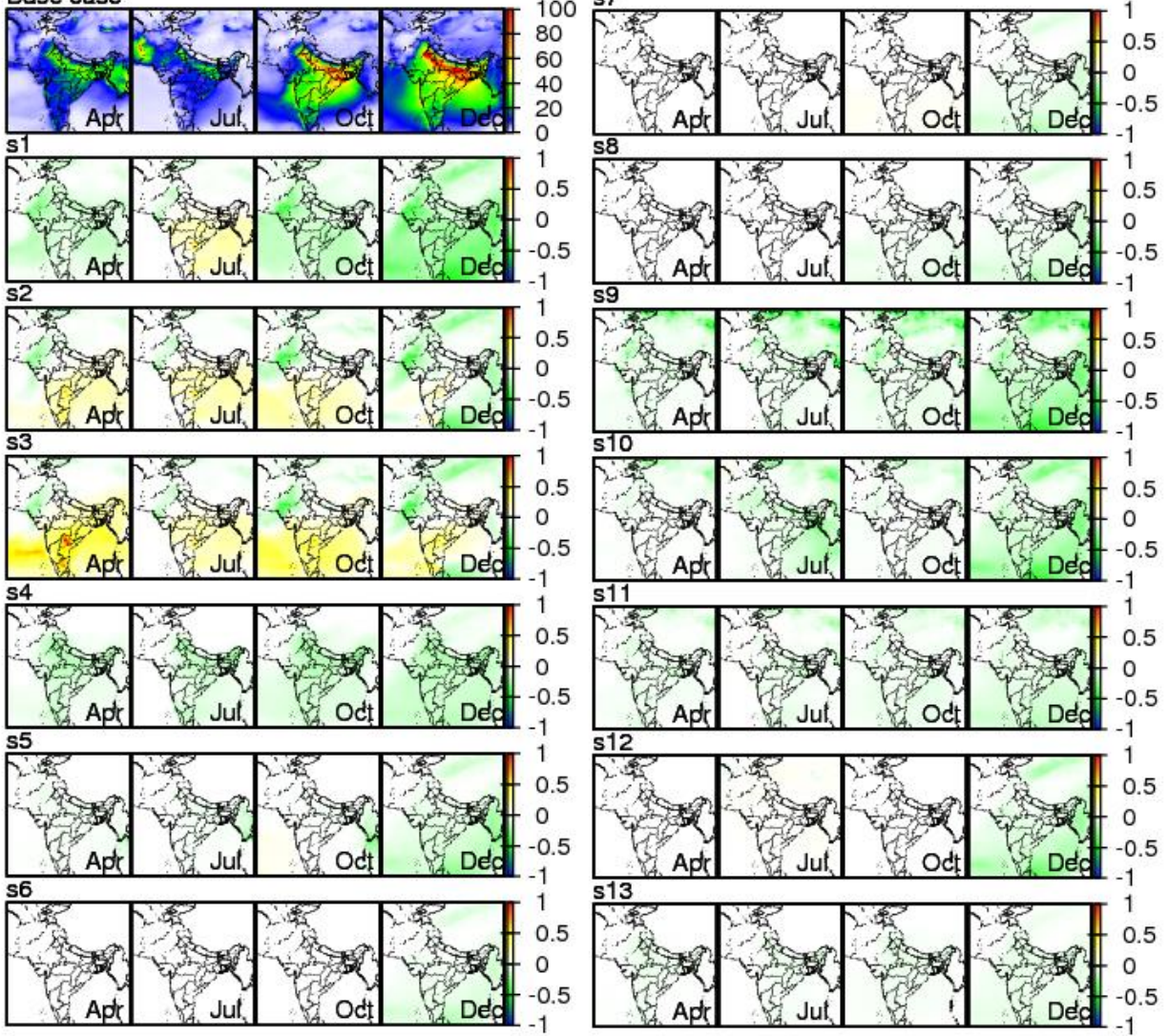
Figure 38. Seasonal variation in predicted concentrations of PM$_{2.5}$ in India in 2015 of base case and different emission scenarios in 2022 in percentage.
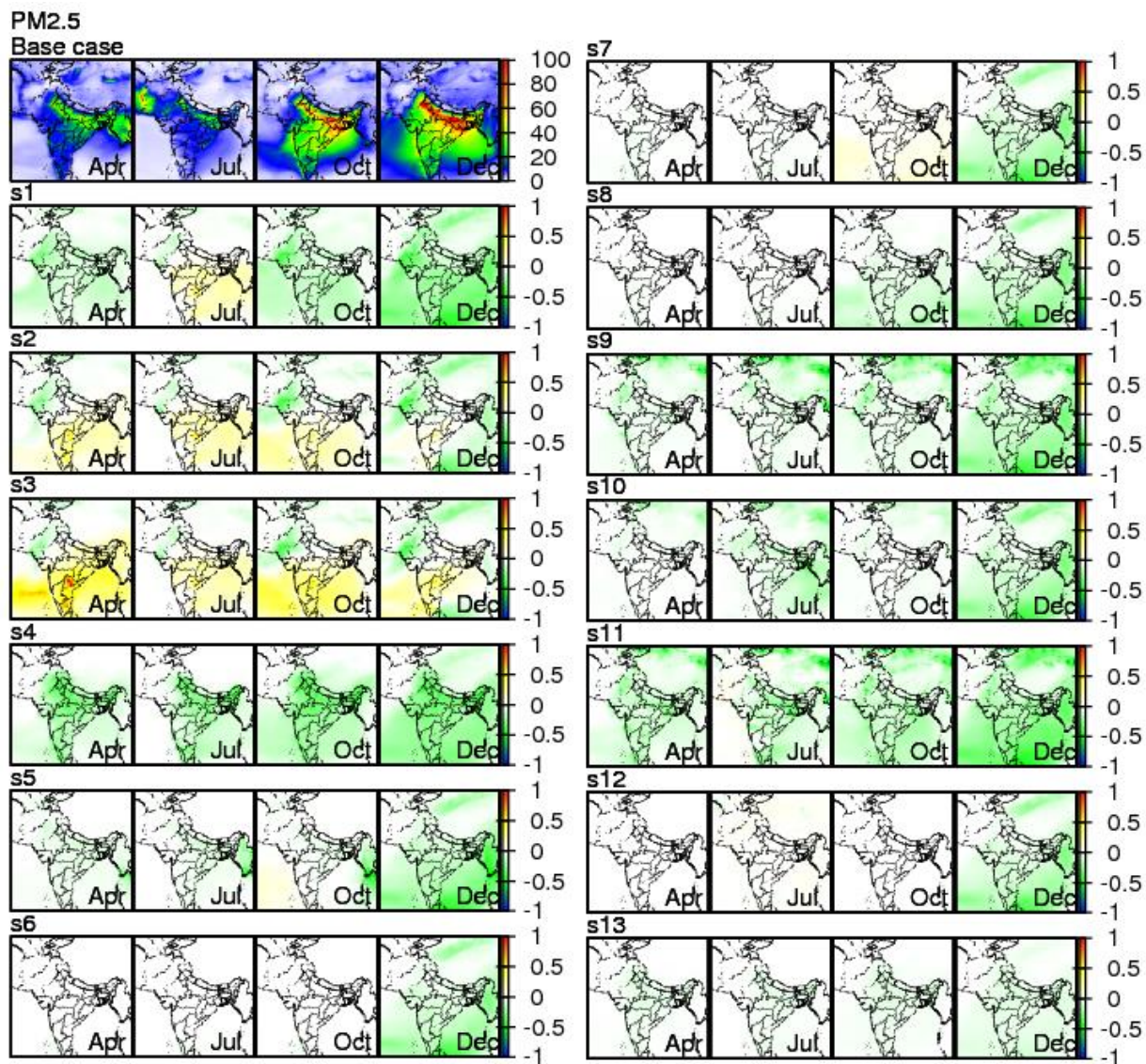
Figure 39. Seasonal variation in predicted concentrations of PM$_{2.5}$ in India in 2015 of base case and different emission scenarios in future in percentage

Table 19. National population averaged concentrations ($\mu g/m^3$) of $PM_{2.5}$ in India under different emission scenarios.

| Scenario	Scenario description	Population averaged concentration($\mu g/m^3$)	Difference (Scenario-base case)
Base Case		32.78	N/A
S1	Implement power plant emission standards - operating	30.95	1.83
S2	Non-implementation of power plant emission standards - under construction	33.50	-0.72
S3	Implement planned coal-fired power plants	34.50	-1.72
S4	Reduce household solid fuels	30.51	2.27
S5	Reduce crop burning	31.82	0.96
S6	Reduce municipal solid waste burning	31.98	0.80
S7	Vehicle emissions standards	31.87	0.91
S8	Slower oil consumption growth	32.44	0.34
S9	Shift to Zigzag kilns	31.39	1.39
S10	Stronger oil sulfur limits - industry	30.69	1.09
S11	New emission standards - industry	29.83	2.95
S12	Dust control - construction	32.08	0.70
S13	Reduce diesel generating sets use	32.34	0.43
S_all	**Combination of all the scenarios**	**20.11**	**12.67**

Table 20. Total premature mortality (x10^4) in India under different emission scenarios with uncertainty range in future.

| Scenarios	Scenario description	Premature mortality (10^3 deaths)	Difference (Base case-scenario, 10^3 deaths)
base	N/A	1461.8 (746.6, 2180.4)	N/A
S1	Implement power plant emission standards - operating	1351.3 (637.8, 2087.8)	110.5
S2	Non-implementation of power plant emission standards - under construction	1475.6 (754.9, 2234.5)	-13.8
S3	Implement planned coal-fired power plants	1488.0 (766.8, 2253.6)	-26.2
S4	Reduce household solid fuels	1284.9 (604.3, 1943.2)	176.9
S5	Reduce crop burning	1407.0 (708.1, 2005.1)	54.8
S6	Reduce municipal solid waste burning	1416.3 (723.7, 2054.5)	45.5
S7	Vehicle emissions standards	1414.5 (722.4, 2052.5)	47.3
S8	Slower oil consumption growth	1429.2 (754.4, 2131.4)	32.6
S9	Shift to Zigzag kilns	1379.1 (652.9, 2105.6)	82.7
S10	Stronger oil sulfur limits - industry	1408.7 (669.6, 2144.3)	53.1
S11	New emission standards - industry	1277.8 (597.9, 1971.5)	184.0
S12	Dust control - construction	1420.2 (675.7,2159.8)	41.6
S13	Reduce diesel generating sets use	1431.9 (756.3, 2153.6)	29.9
S_all	**Combination of all the scenarios**	**602.9 (301.3, 905.6)**	**858.9**
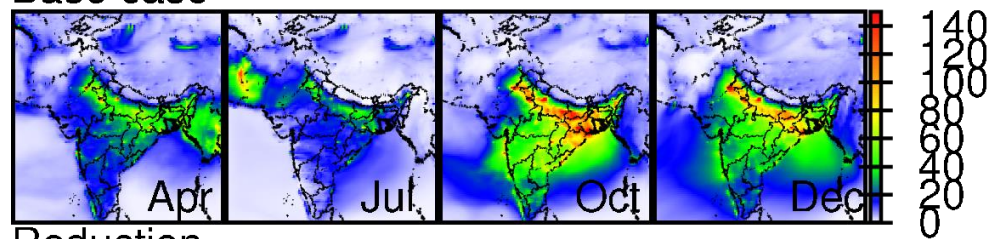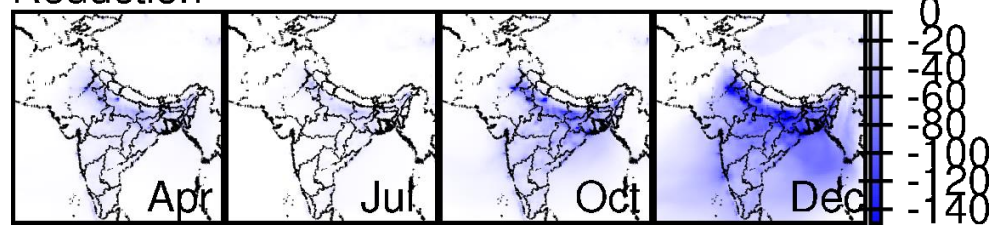
Figure 40. Seasonal variation in total reduction of PM$_{2.5}$ in India in 2015 of combination of all the emission scenarios in future (Units are in µg/m^3).
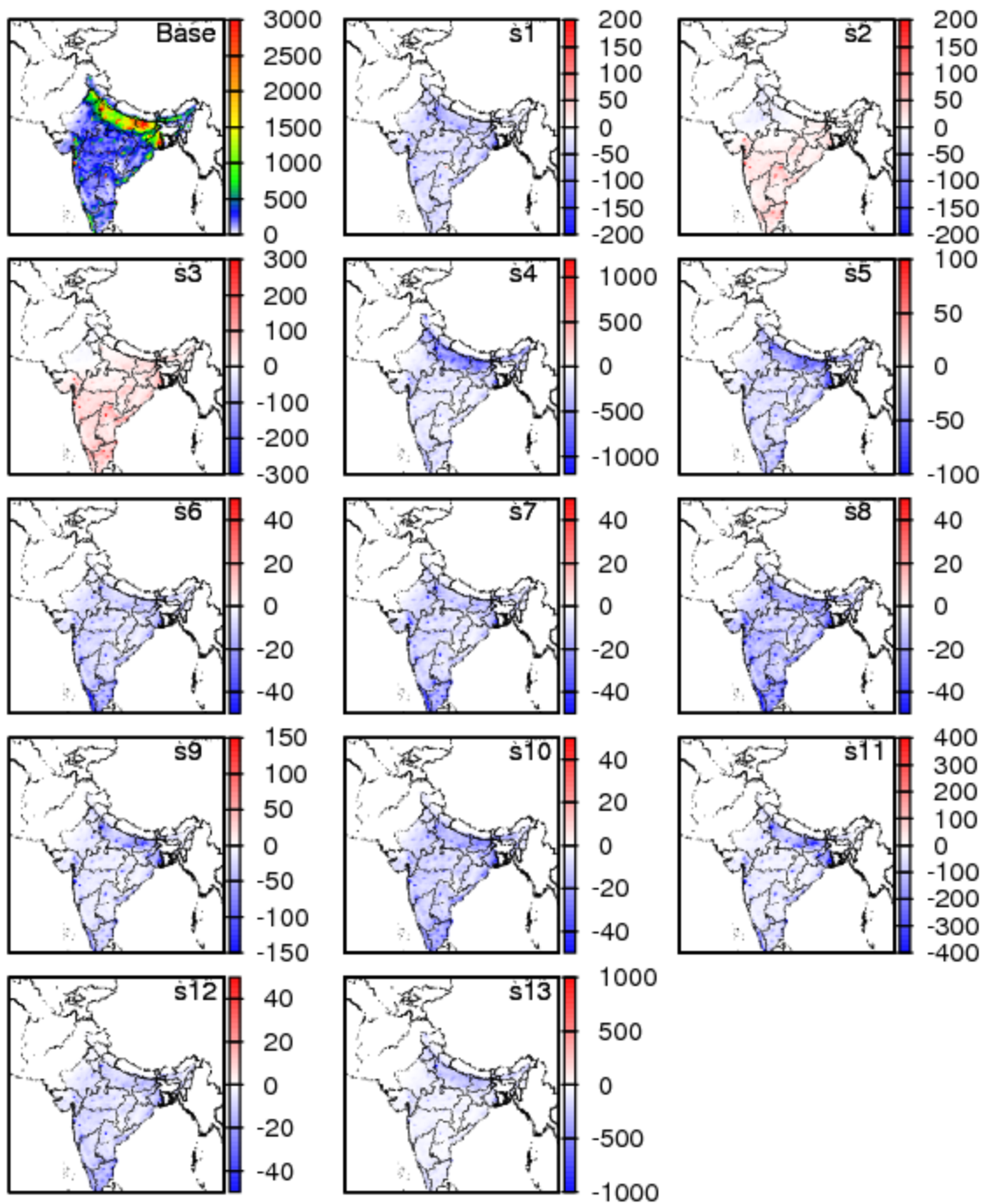
Figure 41. Total premature mortality of basecase (2015) and reductions on future scenarios.

5. Summary

In this report, source-oriented versions of the Community Multi-scale Air Quality (CMAQ) model with anthropogenic emissions from Emissions Database for Global Atmospheric Research (EDGAR), biogenic emissions from the Model for Emissions of Gases and Aerosols from Nature (MEGAN) v2.1, and meteorology from the Weather Research and Forecasting (WRF) model 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 major components including primary PM (PPM) and secondary inorganic aerosol (SIA) in India in 2015. Then, the health risks were estimated based on the predicted PM$_{2.5}$ concentrations and the air quality benefits from potential policy interventions in future were analyzed.

In the severe polluted area from North India to South India, the major contributors are energy, industry, residential and agriculture. Windblown dust makes a high contribution to total primary particulate matter (PPM) in some areas outside India like Tibet and Iran. Residential and agriculture contribute almost all the ammonia PM, especially at the high concentration area from North India to South India. Energy, industry and on-road contribute almost of nitrate PM especially at the high concentration area from North India to South India. In contrast to ammonia PM, energy nitrate PM concentrations are also high in Central India. Energy, industry and background & primary sulfate PM are major contributors to total sulfate PM. Energy sulfate PM concentrations are higher in South and Central India and industry sulfate PM concentrations are higher in East India.

The major source of PPM mass is from within the state. In the selected cities, Chandigarh is the capital of the northern Indian states of Punjab and Haryana, Jaipur is the capital of India's Rajasthan state, and Lucknow is the capital of the state of Uttar Pradesh and Delhi. About 80% of PPMs are from within the state in these 4 cities. Similar to PPM analysis, 80% of the total ammonia PM concentrations are from within the state, but Delhi have 20% of the total ammonia PMs from the adjacent states: Haryana, Rajasthan, U.Pradesh and Uttarakhand. In contrast, the nitrate PM in Delhi comes from 3 sources: sources from within the state, Haryana & Rajasthan and Punjab, Himachal Pradesh and Jammu&Kashmir. Each region contributes ~25% to total nitrate PM in Delhi. In other 3 cities, sources from within the state dominates total nitrate PM concentrations. The sulfate PM in 4 cities mainly comes from primary sources (~40%, 70% in

Delhi). However, the secondary sulfate PM is more likely from within the state in Lucknow and Jaipur.

In major urban areas where population density is high, the total premature mortality associated with PM exposure can be much greater than 3000 cases per year per grid cell (i.e., 36 km $\times$ 36 km). High premature mortality occurs in the Indo-Gangetic plains and East India. The estimated national $PM_{2.5}$ related premature mortalities for adults $\geqslant$ 25 years old in 2013 is approximately 1.46 million with CI95 of 0.75-2.18 million. . Residential followed by Industry, Agriculture, Energy were the major sources contributing to premature mortality due to $PM_{2.5}$ concentration. Majority of premature mortality in all the states apart from the ones which didn't had any source information were observed to be contributed by residential sources (above 1500).

National population-averaged concentrations of $PM_{2.5}$ in India under 13 emission scenarios were estimated. In total, these measures could reduce the average $PM_{2.5}$ levels by 40% nationwide, leading to 858,900 avoided premature deaths per year.

The combined effect of the power sector measures (implementing emissions standards in operating and new coal-based thermal power plants and canceling planned plants not yet under construction, scenarios S1-3) had the largest effect on reducing $PM_{2.5}$ by 4.3 $\mu g/m^3$. Applying new emission standards in industry (S11) was the second largest at a reduction of 2.95 $\mu g/m^3$. The results show that reducing residential emission from solid fuels combustion, reducing power sector emissions and reducing diesel generating sets use affect $PM_{2.5}$ concentration most, followed by reducing municipal solid waste burning and new emission standards applying in industry sector. In scenarios of thermal power plants emission, concentration increased maximum to more than 9 $\mu g/m^3$ and decreased greatly in part of north India. From results, residential emission reduction could greatly eliminate $PM_{2.5}$ concentration, followed by implementing new emission standards in the power sector and introducing new emissions standards for the industrial sector.

Acknowledgement

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Glossary & Definition

Terms	Definition
AERO5	A new aerosol module employs a modal approach to represent the size distribution of particulate matter
AERO6	An updated aerosol module requires additional PM Species.
CMAQ	Community Multi-scale Air Quality (CMAQ) modeling system
domain	A geographic area which identified in research area with certain resolution
EC	Elemental carbon
EDGAR	Emissions Database for Global Atmospheric Research
FINN	Fire Inventory from NCAR
LAI	Leaf area index
MCIP	Meteorology-Chemistry Interface Processor, used to generate meteorological CMAQ inputs
MEGAN	Model for Emissions of Gases and Aerosols from Nature
MNB	Mean normalized bias
NMVOC	Non-methane volatile organic compounds
NOx	Generic term for the mono-nitrogen oxides NO and NO2
OC	Organic carbon
Open burning	Satellite detected biomass burning biomass, which includes wildfire, agricultural fires, and prescribed burning and does not include biofuel use and trash burning.
PM	Particulate matter
PM_{10}	Particles less than 10 micrometers in diameter
$PM_{2.5}$	Particles less than 2.5 micrometers in diameter
POA	Primary organic aerosol
POC	Primary organic carbon
PPM	Primary particulate matter
SAPRC-11	Aromatics and Aromatic SOA Mechanisms. A new version of the SAPRC aromatics mechanism updates are restricted to aromatic chemistry.
SAPRC-99	The SAPRC-99 detailed atmospheric chemical mechanism for VOCs and NOx incorporates recent reactivity data from a wide variety of VOCs.
SOA	Secondary organic aerosol
SPECIATE 4.3	A speciation profile data base developed by the US EPA
VOC	Volatile organic compounds
WRF	Weather Research & Forecasting model