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Monthly and spatially resolved black carbon emission inventory of India: uncertainty analysis

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Abstract. Black carbon (BC) emissions from India for the year 2011 are estimated to be $901.11 \pm 151.56\,\mathrm{Gg\,yr^{-1}}$ based on a new ground-up, GIS-based inventory. The grid-based, spatially resolved emission inventory includes, in addition to conventional sources, emissions from kerosene lamps, forest fires, diesel-powered irrigation pumps and electricity generators at mobile towers. The emissions have been estimated at district level and were spatially distributed onto grids at a resolution of $40 \times 40\,\mathrm{km}^2$. The uncertainty in emissions has been estimated using a Monte Carlo simulation by considering the variability in activity data and emission factors. Monthly variation of BC emissions has also been estimated to account for the seasonal variability. To the total BC emissions, domestic fuels contributed most significantly (47 %), followed by industry (22 %), transport (17 %), open burning (12 %) and others (2 %). The spatial and seasonal resolution of the inventory will be useful for modeling BC transport in the atmosphere for air quality, global warming and other process-level studies that require greater temporal resolution than traditional inventories.

1 Introduction

Carbonaceous aerosols, defined as black carbon (BC) and also known as elemental carbon (EC) and organic carbon (OC) (Pachauri et al., 2013), form a significant and highly variable component of atmospheric aerosols. Neither BC nor OC has a precise chemical definition. OC includes numerous organic compounds, some of which are found to be carcinogenic, such as poly-aromatic hydrocarbons (PAHs) (Menzie et al., 1992; Pedersen et al., 2005). The Intergovernmental Panel on Climate Change (IPCC) defines BC as "Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability" (IPCC, 2013). BC is released from incomplete combustion of carbonaceous fuels such as agricultural and forest biomass, coal, diesel, etc. The type of combustion greatly affects the BC emission rates; notably, inefficient combustion emits more BC than efficient combustion for the same type of fuel. Aside from air quality and health effects, there are a number of climate impacts of BC emissions including alterations to temperature through atmospheric adsorption, modifications to precipitation timing and increased melting of snow (Meehl et al., 2008; Flanner et al., 2007; Ramanathan and Carmichael, 2008; Quinn et al., 2007; Koch and Del Genio, 2010; Bond et al., 2013), all of which are consequential to global warming. BC has been implied to be the second-largest contributor to global warming after CO_2 (Ramanathan and Carmichael, 2008). There is a current debate that due to the short life span of BC, the BC atmospheric concentration will drop quickly if emissions are reduced, thereby potentially offering a rapid means to slow down global warming (Bond and Sun, 2005; Grieshop et al., 2009; Kopp and Mauzerall, 2010; Bowerman et al., 2013).

India is a rapidly growing economy with massive future growth potential. The total energy and coal consumption has almost doubled from 2001 to 2011 (IEA, 2012). The emissions of particulate matter or aerosols have been rising over the last few decades and are expected to increase in the future as well, due to rapid industrial growth and slower emission control measures (Menon et al., 2010). Recent studies (Yasunari et al., 2013; Lau et al., 2010) have shown that the deposition of BC in the Himalayan glaciers has accelerated their melting. While BC is a source of warming on a global scale, on a regional scale, it has adverse effects on air quality and human health. BC is a major part of particulate matter, with a size less than 2.5 micron ($PM_{2.5}$), and like other $PM_{2.5}$ particles, it is small enough to be inhaled. According to the World Health Organization (WHO), exposure to BC can lead to cardiopulmonary morbidity and mortality. WHO also suggests that BC may act as a universal carrier of chemicals of varying toxicity to lungs (Janssen et al., 2012). Understanding the sources of BC, their emissions and spatial distribution is important both for policy making and improving climate modeling. Preparation of an accurate emission inventory is the first step towards developing robust air pollution control strategies. Air quality measurement stations are installed at limited locations and are unable to provide a measure of spatial variability. However, observations coupled with air quality models can provide comprehensive information about the impact of various sources on ambient air quality and their spatial variability. The greatest benefit of these models is gained after preparing an accurate emission inventory, validating the models with observations and thereby enabling a tool for improved control measures.

Although there have been several emission inventories developed for BC in the last decade, the estimates are variable without any knowledge of uncertainties. Model-predicted BC concentrations over India are 2 to 6 times lower than the observed concentrations (Ganguly et al., 2009; Nair et al., 2012; Bond et al., 2013; Moorthy et al., 2013). Further the current estimates vary considerably. The Reanalysis of tropospheric chemical composition (RETRO) emission inventory (Schultz et al., 2007, 2008) estimated BC emissions in 2010 as 697 $Gg\,yr^{-1}$; the System of Air Quality Weather Forecasting and Research (SAFAR) emission inventory (Sahu et al., 2008) estimated them as 1119 $Gg\,yr^{-1}$ for the year 2011; Klimont et al. (2009) report BC emissions as 1104 $Gg\,yr^{-1}$ for the year 2010, and Lu et al. (2011) reported them as 1015 $Gg\,yr^{-1}$ for the year 2010. Not only is there a need to get a meaningful total estimate but there is also a need to assess the uncertainty and spatial variability associated with these estimates. Most of the emission inventories provide yearly emissions and do not account for sub-annual temporal emission variability, which leads to inaccurate impact assessments. To improve the nature of advanced numerical forecasts of impacts from aerosol pollution, we have developed an emission inventory at a monthly resolution.

The objective of this study is to prepare a sub-annual, high spatial resolution, comprehensive spatially gridded emission inventory of BC emissions for India for the base year 2011. The approach is a ground-up inventory based on activity data from various sectors, combined with emission factors. While results are provided for 1 year, the frequency and distribution should be general enough such that coupled with growth forecasts, multiyear use could be valid. In this study, we have prepared a district-wise emission inventory available on a $40 \times 40\,km^2$ grid. We have accounted for all the major sources of BC emissions in India. For example, emissions from kerosene lamps (Lam et al., 2012) and forest fires, which were previously unaccounted for in many emission inventories, have been included. Monthly variation of BC emissions has also been estimated to provide better input for air quality models. We employ a unique approach to quantify uncertainty in the emissions by considering variability in (i) activity data from various sources and (ii) emission factors (EFs). Specifically, probabilistic distributions were assigned to both activity data and EFs. By employing a Monte Carlo simulation, several activity levels and EFs were generated to arrive at emissions (by multiplying generated activity data and EF), which could be interpreted in terms of a mean value and associated uncertainty.

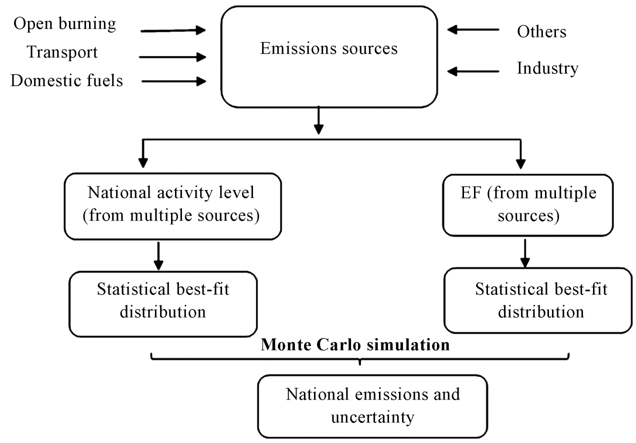

Figure 1. Methodology for national emissions.

In Sect. 2 we present the methods used in our analysis. Sect. 3 describes the source sectors and activity data we considered. A description of the magnitude of emissions from each sector is presented in Sect. 4.

2 Methods

Our approach may be divided into two parts. Figure 1 presents the methodology for developing national emissions and their uncertainty, and Fig. 2 presents the approach for extracting gridded emissions. For estimating national emissions, a thorough review of multiple national activity data and EFs for each source was conducted from available published and unpublished sources (Table 1 and Table 2).

We fit a probability distribution function (PDF) to both national activity data and EFs from a pool of distributions on the basis of a Kolomogorov–Smirnov test (KS statistic) using Mathwave Technologies EasyFit© software (Mathwave Technologies, 2015). Using the optimal PDF for both variables (EFs and activity data) for each source, we generated 1000 estimates of each variable from each of the two distributions. Further increasing the number of generations did not change the mean and the variance of the emissions.

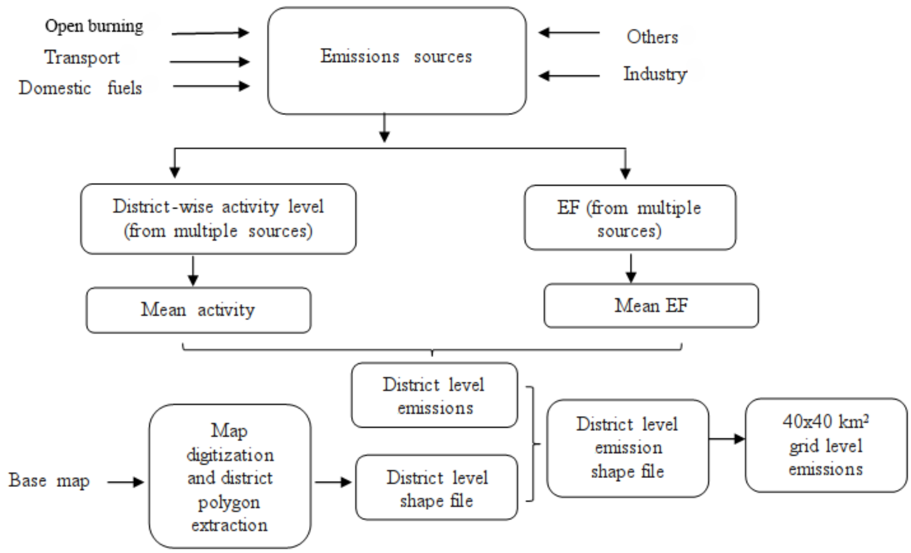

Figure 2. Methodology for preparing gridded emissions.

For activity data that had only one source of information, a normal distribution with a mean as the data point and standard deviation of 20 % of the data point was assumed based on the experience regarding other data sets (Table 1). Best-fit distributions were only determined from the KS statistic if the number of data points exceeded five; in other cases, a uniform distribution was assumed.

For preparing the gridded inventory, the emissions were first estimated within a Geographic Information System (GIS) using polygons at the district level. Polygons were subsequently divided into $40 \times 40\,km^2$ grid elements and were proportionally assigned emissions based on the area. The area for grid elements spanning a district border was accounted for. Emissions from industry (point data) were added directly to the overlying grid based on available location coordinates for the source. For the road transport (network) sector, the data from at the district level were distributed along the road network and then assigned to overlying grids, proportionally to the length of road in the grid element. Interpolation of the data was not conducted, as this would lead to erroneous georeferencing of emissions, particularly in the case of point data. More details are found in the subsections below.

For the national level annual inventory, Monte Carlo simulations were undertaken to specifically estimate mean emissions and uncertainties, whereas at the district level the mean of the EFs and district level activity data were used to arrive at average emission levels. An image of the political map of India (Census of India, 2011) was georeferenced using Google Earth, and 640 districts were digitized as polygons to generate a national level shapefile. This shapefile had an attribute table containing all the districts, and yearly emission quantities were recorded for each district. The shapefile and polygon data were resampled to a $40 \times 40\,km^2$ grid by calculating the area of each portion of the districts within a grid element and attributing that portion of the emissions to the grid. As a grid cell may overlay over more than one district, the overall emission in each cell was calculated by summing up part of emissions from each contributing portion from the district, based on area of the district within the grid cell and emission density for the district:

$$E_{cell} = \sum_{i=1}^{n} (\rho_i \cdot A_i), \tag{1}$$

where n is the total number of districts within each grid cell, ρ is the emission density ($g\,s^{-1}\,m^{-2}$) for each district and A is the area of the district (m^2) within the grid. Emission density (mass / time area) was calculated by dividing the BC emission in the district with the total area of the district.

3 Source sectors and activity data

The emissions sources considered in this study can be broadly categorized into five sectors: open burning, industry, transport, domestic fuel and others. In the following section we define the activity data and emission sources considered within each sector. All the emission sources identified by Reddy and Venkataraman (2002a, b) and Sonkar (2011) were included in this study. Also, some of the highly emitting sources identified in the recent literature (kerosene lamps, diesel generators and irrigation pumps) were also considered. Tables 1 and 2 provide an overview of activity data and EFs for the sources considered.

Table 1. Mean activity data, standard deviation and best-fit probabilistic distribution.

Subsector	Activity level	Mean ± SD	Distribution
Open burning (Mt yr^{-1})			
Crop residue burning	99.93[1,2], 89.79[1,3], 90.94[1,4]	93.56 ± 4.96	Uniform
Forest fire*	47.83[5]	47.83 ± 9.56	Normal
Garbage burning	3.90[2,6], 2.51[2,6,7,8,9]	3.2 ± 0.76	Uniform
Industry (Mt yr^{-1})			
Brick*	474[10]	474 ± 237	Normal
Steel*	40.05[11]	40.05 ± 8.01	Normal
Sugar*	77.1[12,13]	77.1 ± 15.42	Normal
Cement*	28.06[14]	28.06 ± 5.61	Normal
Power coal*	380.91[15]	380.91 ± 76.18	Normal
Power diesel*	0.71[15]	0.71 ± 0.01	Normal
Transport (billion km yr^{-1})			
Bus	38.77[16,17], 39.3916[16,18],32.8316[16,19]	35.46 ± 3.94	Uniform
Car	128[16,17],196.27[16,18], 130.85[16,19], 167.87[16,21]	155.06 ± 29.76	Uniform
LMV	104.22[16,17], 131.51[16,18], 65.75[16,19]	105.32 ± 22.74	Uniform
LCV	78.55[16,17], 99.12[16,18], 74.34[16,19]	111.37 ± 38.70	Uniform
Truck	122.99[16,17], 87.30[16,20], 125.50[16,21]	109.60 ± 16.72	Uniform
Taxi	38.25[16,17], 40.26[16,18], 48.32[16,19], 16.91[16,21], 60.44[16,22], 51.01[16,23]	42.52 ± 14.86	Gumbel
Two wheeler	450.8[16,17], 764.07[16,18], 481.36[16,21], 2062.89[16,22], 313.26[16,23]	814.50 ± 716.18	Uniform
Tractor and trailer	11.08[16,17], 26.38[16,18]	18.73 ± 8.38	Uniform
Railway coal (kt yr^{-1})*	1[24]	1 ± 0.02	Normal
Railway diesel (kt yr^{-1})*	21.06[24]	21.06 ± 42.10	Normal
Shipping HSDO (kt yr^{-1})*	0.11[25,26]	0.11 ± 0.02	Normal
Shipping fuel oil (kt yr^{-1})*	80[25,26]	80 ± 16	Normal
Shipping LDO (kt yr^{-1})*	0.36[25,26]	0.36 ± 0.07	Normal
Aviation LTO (kt yr^{-1})*	514.16[2,25,27,28]	514.16 ± 102.83	Normal
Aviation cruise (kt yr^{-1})*	1505.83[2,25,27,28]	1505.83 ± 301.16	Normal
Domestic fuel (Mt yr^{-1})			
Dung cake	144.84[29], 75.62[30]	110.23 ± 37.91	Uniform
Agriculture residue	125.34[29], 81.25[30]	103.30 ± 24.14	Uniform
Firewood	209.99[31], 281.99[29], 193.87[30]	228.62 ± 41.96	Uniform
Coal*	4.77[31]	4.77 ± 0.95	Normal
Kerosene cooking*	4.57[31,32]	4.57 ± 0.91	Normal
LPG*	12.37[31]	12.37 ± 2.47	Normal
Kerosene lamps	1.68[32],1.21[31,32]	1.45 ± 0.25	Uniform
Others (Mt yr^{-1})			
Irrigation pumps*	2.11[25]	2.11 ± 0.42	Normal
Diesel generators (mobile towers)*	1.12[25,33]	1.12 ± 0.22	Normal
Diesel generators (other)*	2.28[25,33]	2.28 ± 0.45	Normal

[1] Ministry of Agriculture (2013). [2] IPCC (2006). [3] Jain (2014). [4] Venkataraman et al. (2005). [5] Land Processes Distributed Active Archive Center (LP DAAC). [6] CPCB (2007). [7] Kumar (2010). [8] National Environmental Engineering Research Institute (NEERI). [9] CPCB (2012). [10] Industry experts. [11] Press Information Bureau (2011). [12] DAC (2013). [13] ISMA (2012). [14] CMA (2012). [15] CEA (2012). [16] Ministry of Road Transport and Highways (2011). [17] Baidya and Borken-Kleefeld (2009). [18] Ramachandra et al. (2015). [19] Guttikunda and Calori (2013). [20] Mittal and Sharma (2003). [21] Ramachandra and Shwetmala (2009). [22] Sindhwani and Goyal (2014). [23] Pandey and Venkataraman (2014). [24] Ministry of Railways (2012b). [25] MoPNG (2013). [26] EEA (2013). [27] ICAO (2010). [28] DGCA (2013). [29] Yevich (2003). [30] Smith et al. (2000). [31] MoSPI (2014b). [32] Lam et al. (2012). [33] Shakti Sustainable Energy Foundation (2014). * Normal distribution assumed.

Table 2. Mean EFs, standard deviation and best-fit probabilistic distribution.

Subsector	EFs used	Mean EF ± SD	Best-fit distribution
Open burning (g kg^{-1})			
Crop residue burning	0.69[1], 0.78[2], 0.73[3], 0.47[4], 0.75[2]	0.69 ± 0.19	Dagum
Forest fire	0.56[1], 0.98[4], 0.99[5], 0.56[6]	0.76 ± 0.21	Error
Garbage burning	0.65[7], 0.37[8]	0.51 ± 0.15	Uniform
Industry (g kg^{-1})			
Brick	0.11[9], 0.27[9], 0.09[9]	0.16 ± 0.09	Uniform
Steel	0.32[3], 1.1–1.58[10], 0.224[11], 0.23–0.13[12], 0.06[5], 0.0095[13]	0.45 ± 0.51	Log Pearson 3
Sugar	1.2[14], 0.7[15]	0.95 ± 0.27	Uniform
Cement	0.32[3], 1.1–1.58[10], 0.224[11], 0.23–0.13[12], 0.06[5], 0.0095[13]	0.45 ± 0.51	Log Pearson 3
Power coal	0.003–0.032[16], 0.077[13], 0.0029[11], 0.002[5], 0.06[5]	0.03 ± 0.03	Gamma (3P)
Power diesel	0.25[11], 0.15[8], 0.06[13]	0.15 ± 0.08	Uniform
Transport (g km^{-1})			
Bus	0.35[17,18], 0.8[18,19], 0.225[18,20], 0.61[18,21]	0.49 ± 0.24	Uniform
Car	0.16[22], 0.17[17,18], 0.05[18,19], 0.07[18,20], 0.16[18,21]	0.09 ± 0.06	Uniform
LMV	0.16[22], 0.138[17,18], 0.17[18,21]	0.15 ± 0.01	Uniform
LCV	0.27[17,18], 0.13[18,19], 0.16[18,21]	0.19 ± 0.07	Uniform
Truck	0.61[17,18], 0.26[18,19], 0.19[18,20], 0.31[18,21]	0.34 ± 0.17	Uniform
Taxi	0.01[22], 0.06[17,18], 0.076[18,20], 0.057[18,21]	0.05 ± 0.03	Uniform
Two wheeler	0.013[23], 0.012[17,18], 0.038[18,19], 0.023[18,20]	0.02 ± 0.01	Uniform
Tractor and trailer*	1.24[23]	1.24 ± 0.25	Normal
Railway coal (g kg^{-1})	1.83[13], 3[8]	2.415 ± 0.33	Uniform
Railway diesel (g kg^{-1})	1.53[24], 0.51[8], 0.29[13]	0.78 ± 0.59	Uniform
Shipping HSDO (g kg^{-1})	0.85[25], 1.19[8], 1.32[26], 0.36[25]	0.78 ± 0.49	Gen. extreme value
Shipping fuel oil (g kg^{-1})	0.38[25], 0.36[25], 0.97[25], 0.85[25], 1.19[8], 1.32[26]	0.72 ± 0.40	Wakeby
Shipping LDO (g kg^{-1})	0.85[25], 1.19[8], 1.32[26]	0.89 ± 0.46	Uniform
Aviation LTO (g kg^{-1})	0.08–0.1[27]	0.09 ± 0.01	Uniform
Aviation cruise (g kg^{-1})	0.02–0.1[27]	0.06 ± 0.02	Uniform
Domestic fuel (g kg^{-1})			
Dung cake	0.53[8], 1[14], 0.8[28], 0.25[4], 0.49[29], 0.18[30], 0.12[31], 0.4[15]	0.47 ± 0.31	Gen. extreme value
Agriculture residue	0.43[32], 0.66[11], 0.75[2], 0.47[4], 0.37[29], 1[8], 1.3[33], 0.24[30], 1.38[34], 0.6[31], 0.9[31]	0.74 ± 0.37	Gen. extreme value
Firewood	1[3], 0.59[1], 0.41[4], 0.7[32], 1.2[14], 1[28], 0.85[8], 0.6[31], 0.35[29], 1.1[33], 0.25[30], 0.83[35], 1.33[6], 0.7[36]	0.78 ± 0.32	Gen. extreme value
Coal	1.91[3], 2.84[10], 1.83[4], 5[8], 0.28[37], 2.295[24], 0.8[11], 0.3[11], 0.69[11], 0.79[11], 0.32[11], 0.497[11], 0.07[36], 5.4[15]	1.64 ± 1.73	Pearson 6 (4P)
Kerosene cooking	0.16[4], 0.02[15]	0.18 ± 0.02	Uniform
LPG	0.067[11], 0.01[15]	0.04 ± 0.03	Uniform
Kerosene lamps	66[38], 89[38], 72[38], 110[38], 79[38], 94[38], 89[38], 76[38]	84.37 ± 14.05	Pearson 6 (4P)
Others (g kg^{-1})			
Irrigation pumps	3.18[24], 3.96[8]	3.56 ± 0.22	Uniform
Diesel generators	3.41[24], 3.96[8]	3.68 ± 0.16	Uniform

[1] Andreae and Merlet (2001). [2] Turn et al. (1997). [3] Streets et al. (2001). [4] Reddy and Venkataraman (2002a). [5] Qin and Xie (2011). [6] Zhang et al. (2013). [7] Akagi et al. (2011). [8] Bond et al. (2004). [9] Weyant et al. (2014). [10] Cooke et al. (1999). [11] Ni et al. (2014). [12] Novakov (2003). [13] Reddy and Venkataraman (2002b). [14] Liousse et al. (1996). [15] Pandey et al. (2014). [16] Streets et al. (2003). [17] ARAI (2008). [18] Chow et al. (2011). [19] Borken et al. (2008). [20] Baidya and Borken-Kleefeld (2009). [21] Mittal and Sharma (2003). [22] Reynolds and Kandlikar (2008). [23] TERI (The Energy and Resources Institute). [24] Ito and Penner (2005). [25] Lack et al. (2009). [26] Bond et al. (2007). [27] Hendricks et al. (2004). [28] Cachier (1998). [29] Saud et al. (2012). [30] Sen et al. (2014). [31] Habib et al. (2004). [32] Li et al. (2009). [33] Parashar et al. (2005). [34] Shen et al. (2010). [35] Shen et al. (2012). [36] Chen et al. (2009). [37] Chen et al. (2005). [38] Lam et al. (2012). * Normal distribution assumed.

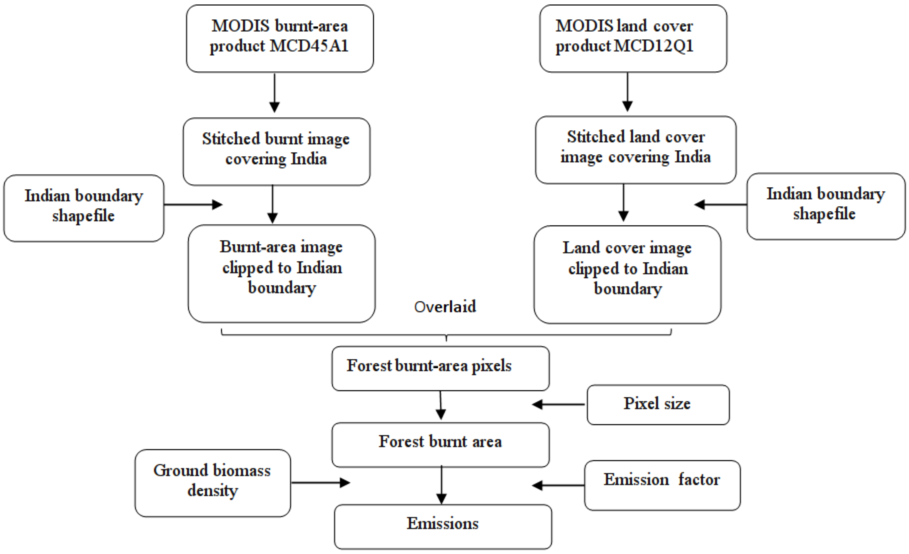

Figure 3. Flow chart for the calculation of forest fire emissions based on MODIS products.

3.1 Open burning

The open-burning sector includes forest fire emissions, open solid-waste burning and agriculture residue burning.

3.1.1 Forest fire

According to the 2013 Forest Survey of India (FSI), around 50 % of the forest area of India is prone to forest fires (FSI, 2013). There is a strong seasonality associated with forest fires in India, with the majority of fires occurring in the months from February to July. The causes of forest fire in India are both man-made and natural, natural causes being the high temperature and low humidity. Man-made causes include accidental fires and forest burnt for shifting cultivation. The forest fire burnt area in this study was determined using the MODIS (Moderate Resolution Imaging Spectroradiometer) monthly burnt-area product MCD45A1, which has a resolution of 500 m (Land Processes Distributed Active Archive Center , LP DAAC). MODIS product MCD12Q1 (500 m resolution) was used to define forest cover. The burnt-area and land cover products were retrieved from the LP DAAC website (https://lpdaac.usgs.gov/).

The methodology used for emission estimation is presented in Fig. 3. The burnt-area (MCD45A1) and land cover product (MCD12Q1) are available in Hierarchical Data Format – Earth Observing System (HDF-EOS) and have an Earth gridded tile area of 1200 km × 1200 km. They were stitched to cover the whole geographical extent of India. The stitched products were converted to GeoTIFF image format and clipped to the Indian domain using the ESRI shapefile of the boundary of India. The same methodology was used for the burnt-area product as well as the vegetation cover. Monthly burnt area GeoTIFF images were overlayed on land cover images to determine the monthly forest burnt-area pixels and subsequently the forest area burnt. Dry mass per unit area of forest burnt was taken to be 5.2 kg m^{-2} (Joshi, 1991). Emissions were distributed district-wise according to the number of incidents of forest fire occurring in that district in 2011. The data of district-wise incidents of forest fire were taken from the most recent forest survey (FSI, 2015). Figure 4 shows the land cover image and burnt-area image used for estimating the forest fire burnt area in January 2011. It can be noted that the emissions from this subsector can easily be updated for future years using the latest MODIS burnt area and land cover products and following the aforementioned methodology.

3.1.2 Municipal solid-waste open burning

The dry weight content of Indian municipal solid waste (MSW) was estimated using the MSW composition in India (CPCB, 2007) and the dry matter content of MSW components per IPCC (2006). Indian MSW is primarily composed of vegetables (40 %), stones (42 %) and grass (4 %), which have a dry matter content of 40, 100 and 40 %, respectively. Dry matter content was estimated to be 67.6 %.

State-wise generated and collected MSW was derived from the Central Pollution Control Board (CPCB) Municipal Solid Waste Management Report 2012 (CPCB, 2012). The MSW generated was distributed among districts according to their urban population. For the states where MSW collected volume was not available, a value of 60 % of the total MSW generated was assumed (Kumar, 2010). The total MSW openly burnt was taken to be 10 % of the collected waste and 2 % of the uncollected waste (National Environmental Engineering Research Institute , NEERI). To provide a second approach for the uncertainty analysis, per capita

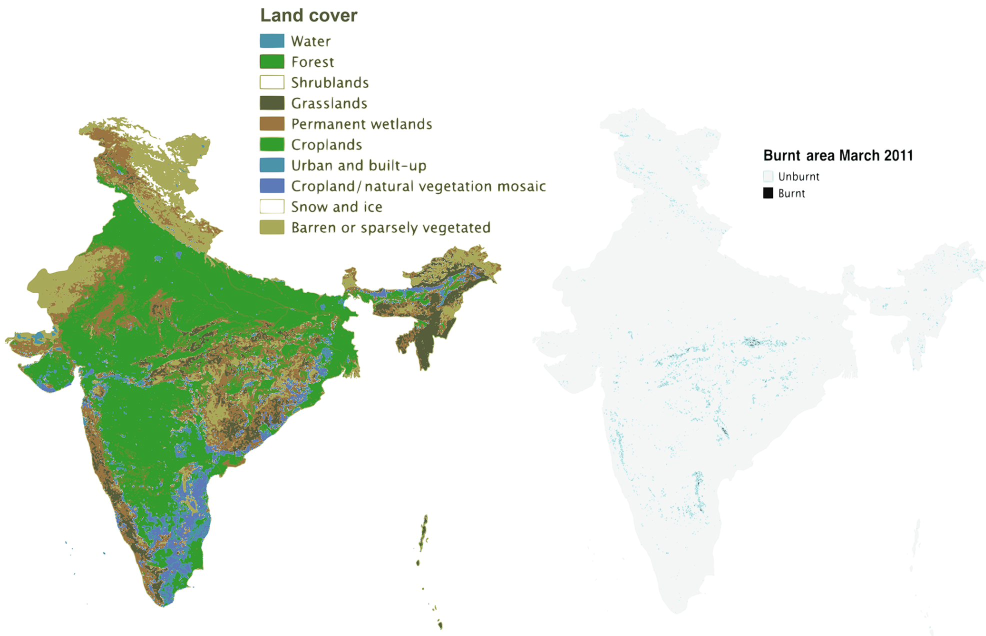

Figure 4. Land cover and burnt area for March 2011.

waste generation in India and the fraction burnt were taken from IPCC (2006). The 2011 census population data were used to provide the urban population of the district. From this, the total MSW burnt for each district was taken as the product of the IPCC guideline results and the urban population.

3.1.3 Agricultural residue burning

India generates a large amount of agricultural residues (e.g., waste biomass) every year after harvesting crops. These residues are used as domestic and industrial fuel, fodder for animals, etc., but a large amount remains unutilized in the fields. The quickest and easiest way for the farmers to manage this waste is to burn it. Figure 5 shows a flowchart for estimating emissions from crop residue burning.

The state-wise production of cotton, jowar, barley, jute, ragi, rice, maize, bajra, groundnut, sugarcane, wheat and rapeseed and mustard in 2011 was taken from the Ministry of Agriculture (2012) (http://eands.dacnet.nic.in/). The crop production was distributed among districts of that state according to the net sown area (Ministry of Agriculture, 2011) in that district. Emission from crop residue burning was calculated using the following equation as suggested by Jain (2014).

$$\mathrm{ECRB} = \sum_{i=1}^{D}\sum_{j=1}^{C}(P \cdot Q \cdot R \cdot S \cdot T \cdot \mathrm{EF}_{\mathrm{BC}}), \quad (2)$$

where ECRB is the emissions from crop residue burning. The summation is done over the districts, D, and for each type of crop, C. The emission is then calculated from the product of crop production (P), residue-to-crop ratio (Q), dry matter fraction (R), the fraction burnt (S), the fraction actually oxidized (T) and finally the EF for BC. Three estimates of crop residue burnt ($P \cdot Q \cdot R \cdot S \cdot T$) were obtained by varying Q, R and S, while holding P and T constant for all the three estimates. In the first estimate, the residue-to-crop ratio (Q), dry matter fraction (R) and fraction burnt (S) were taken from Jain (2014). In the second estimate, the residue-to-crop ratio and dry matter fraction was kept the same and the fraction burnt was taken as 0.25 for all the crops (IPCC, 2006). In the third estimate, the residue-to-crop ratio and dry matter fraction was taken from Venkataraman et al. (2006), and the fraction burnt was kept as 0.25 (IPCC, 2006). This provided us with three estimates of the total crop residue burnt in the fields (Table 1).

3.2 Industry

The industrial sector includes brick production, cement, steel plants, sugar mills and powerplants. In general, emissions and activity data for these sectors are derived from available published reports and scientific literature. We then use location information from each of the facilities to develop district-wise emissions. In order to construct the gridded inventory, industrial units were geolocated precisely using the provided GPS coordinates wherever available. In general, geolocated coordinate data are available for iron and steel manufacturing, cement, sugar mills and power production. Where exact information regarding facility locations cannot be obtained directly, the district-wise distribution is a function of population density. Within the industry sector, this is the case

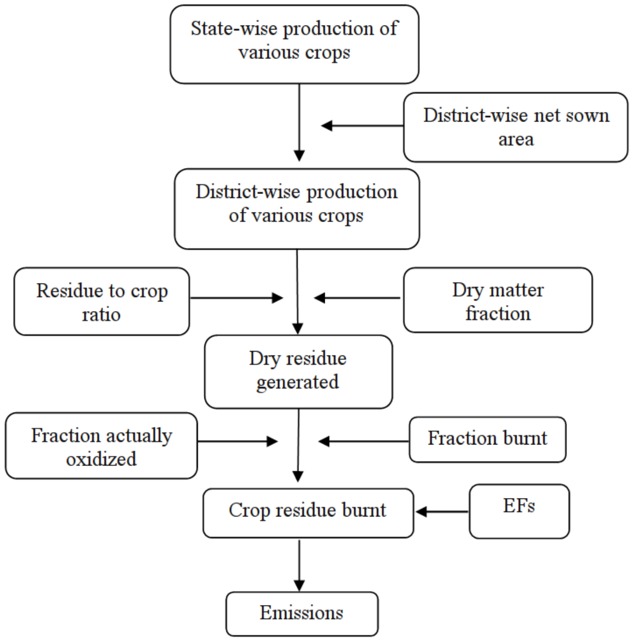

Figure 5. Flow chart for the calculation of agricultural waste burning.

for brick kilns, adding a source of uncertainty to the analysis, but also a novel emission, which previous studies have not included.

3.2.1 Brick industry

The Indian brick industry has more than 100 000 brick kilns producing 250 billion bricks and consuming about 25 million tons of coal annually (Gupta and Narayan, 2010; Maithel et al., 2012). Bricks in India are produced locally in small enterprises on a rural scale (Rajarathnam et al., 2014). It is a seasonal industry operating predominantly from October to June (Maithel et al., 2012). Brick kilns can be classified into two major categories based upon firing practice: intermittent and continuous kilns. Intermittent kilns include clamp, scove, scotch and downdraft kilns (DDK). In these kilns bricks are fired in batches. In continuous kilns brick heating and cooling takes place simultaneously in different parts of the kiln. Several types of kilns, including the Bull trench kiln (BTK), Hoffmann kiln, zigzag kiln, tunnel kiln and vertical shaft brick kiln (Heierli and Maithel, 2015), operate continuously.

In India a majority of the bricks are produced from fixed-chimney Bull trench kilns (FCBTKs) and clamps (Rajarathnam et al., 2014). There are around 60 000 small-scale clamp kilns in India. Located all over India – mostly near or in villages and using biomass, coal and lignite as fuel (Rajarathnam et al., 2014) – these represent an important source of BC emissions. No account of their location, production, fuel consumption and emission factors have been published. For this study, emissions only from FCBTKs are used, which account for 70 % of the total bricks produced from India, and these kilns use coal as the primary fuel (Weyant et al., 2014). The state-wise brick production (in kg) through these kilns was compiled from consultation with industry experts. It was distributed district-wise according to the population of the districts in the state. The quantity produced was assumed to be normally distributed with 50 % standard deviation (Maithel et al., 2012).

3.2.2 Cement manufacturing

The plant-wise cement production in 2011 was taken from the Cement Manufacturers Association, Government of India (CMA, 2012). India had around 150 major cement plants in 2011, which produced 180 million tons of cement and consumed 28 million tons of coal. Cement being a transport-expensive product, plants are evenly distributed across India. Since the plant-wise coal consumption was not available, the national consumption by cement industry was taken from the same source. The fuel consumption was distributed using available location data and based on cement production in 2011.

3.2.3 Iron and steel production

India produced 68.6 million tons of total finished steel in 2010–11, consuming 40 million tons of coal (Ministry of Steel, 2014). The plant-wise steel production was taken from the Press Information Bureau (2011), Government of India. The coal consumption was distributed among plants according to their level of steel production. District-wise coal consumption in steel plants was subsequently determined from the location of these plants.

3.2.4 Sugar mills

India ranks second globally in terms of sugar production. Significant BC emissions result from sugar mills due to the usage of bagasse as a fuel. Bagasse is the fibrous residue obtained from sugarcane juice extraction and consists of cellulose (50 %), hemicellulose (25 %) and lignin (25 %) (Ezhumalai and Thangavelu, 2010; Abhilash and Singh, 2008). India has a total of around 550 sugar mills, which produced 26.3 million tons of sugar by crushing 361 million tons of sugarcane (Indian Sugar Mills Association, ISMA, 2012; DAC, 2013). Specific geolocated data are available and were used to distribute the emissions in the gridded data set. The mill-wise sugarcane crushing capacity was taken from the Department of Food & Public Distribution (DFPD, 2011). The total sugarcane crushed was distributed among mills according to their crushing capacity. The bagasse generated was taken as 30 % of the total sugarcane crushed (Pessoa Júnior et al., 1997).

3.2.5 Powerplants

The Indian Central Electricity Authority (CEA, 2012) reports the plant-wise fuel consumption for coal and diesel powerplants in India. In 2011, India had an installed capacity of 112 GW of coal- and 1.2 GW of diesel-based thermal powerplants. There are around 100 coal-based and 14 diesel-based major thermal powerplants located across India, with location data available from government reports. District-wise fuel consumption was estimated by the location of these plants using the data contained in the report.

3.3 Transport

From the transportation sector emissions from road vehicles, railways, shipping and aviation have been accounted for individually. For road vehicles, to prepare gridded data from district level emissions, road network data from OpenstreetMap© (OpenStreetMap, 2016) were utilized. The data provide a high-resolution road network in vector format. The district shapefile, grid polygons and road network shapefile were resampled to a $40 \times 40\,\mathrm{km}^2$ grid by calculating the total road length in each portion of the districts within a grid element and attributing that portion of the emissions to the grid. For non-road vehicles, the methodology discussed in Sect. 2 was used.

3.3.1 Road vehicles

Road vehicles have been divided into seven categories: two wheelers, cars, light motor vehicles (LMVs), light commercial vehicles (LCVs), taxies, trucks, buses, tractors and trailers.

The state-wise number of registered vehicles in the aforementioned categories was taken from the Ministry of Road Transport and Highways (2011). The vehicles were distributed among districts of that state according to the population of that district. In determining the emissions for 2011, we needed an estimate of the number of vehicles on the road for that year. The reported number of registered vehicles represents the cumulative number of first registrations (Parikh and Radhakrishna, 2005). In India, vehicles are neither deregistered when they are no longer in use nor are double registrations deducted. The actual number of vehicles on the road is significantly smaller than the number of registered vehicles. Baidya and Borken-Kleefeld (2009) determined the rolling fleet in 2005 using survival functions. The category-wise number of vehicles on the road as a fraction of registered vehicles was taken from Baidya and Borken-Kleefeld (2009). Emissions from the road were estimated using the number of vehicles on the road and the annual distance traveled per vehicle type.

$$\mathrm{EV}_{\mathrm{district}} = \sum_{i=1}^{n} (N_i \cdot \mathrm{AKT}_i \cdot \mathrm{EF}_i), \qquad (3)$$

where EV is the total BC emissions from vehicles for a district (g district^{-1} year^{-1}), i is type of vehicle, N is the number of vehicles, AKT is the annual kilometer traveled for the vehicle type (km year^{-1}) and EF is the vehicle type emission factor (g km^{-1}).

The annual average distance traveled is difficult to quantify and is a source of uncertainty in the emissions. The annual distance traveled by various vehicle types was derived from seven different studies (Table 1). This provided us with multiple estimates of the total distance traveled by a vehicle type in a year. For some vehicle types only few BC EFs were available. To compensate for lack of information, EFs were derived from $PM_{2.5}$ emission factors using the BC / $PM_{2.5}$ fraction given by Chow et al. (2011).

3.3.2 Railways

Railways in India are primarily powered by electricity and diesel. The use of coal has decreased over the years and is negligible now. The annual report (2010–11) of Indian railways details the consumption of diesel and coal (Ministry of Railways, 2012b). The state-wise allocation of fuel consumed was performed according to the railway track length in the state (Ministry of Railways, 2012a) and finally district-wise according to the population of the district.

3.3.3 Shipping

The Ministry of Petroleum and Natural Gas (MoPNG) reports the total consumption of fuel oil (FO), high-speed diesel oil (HSDO) and light diesel oil (LDO) by the shipping subsector in 2011 (MoPNG, 2014). According to IPCC guidelines (IPCC, 2006), the fuel used in international bunkers is not counted in the national emission inventory and their estimate is recorded separately. The proportion of shipping fuel used domestically was assumed from the European Environment Agency (EEA, 2013). Due to the nonavailability of a spatial proxy, the emissions from ships have not been distributed district-wise and have only been accounted for in the national emissions.

3.3.4 Aviation

The total aviation turbine fuel (ATF) consumption in India was taken from MoPNG (2014). Domestic operations account for 38 % of the total fuel consumption (ICAO, 2010). Domestic fuel consumption was divided into that used for landing and takeoff (LTO) and for cruise operations. The Directorate General of Civil Aviation (DGCA) reports the total number of domestic scheduled and nonscheduled aircraft departures in 2011 (DGCA, 2013). The fuel consumption per LTO was taken from IPCC (2006). The LTO ATF consumption was distributed district-wise according to the number of flights landing and taking off from the airports in that district. The cruise emission was not distributed and was only counted in national emissions.

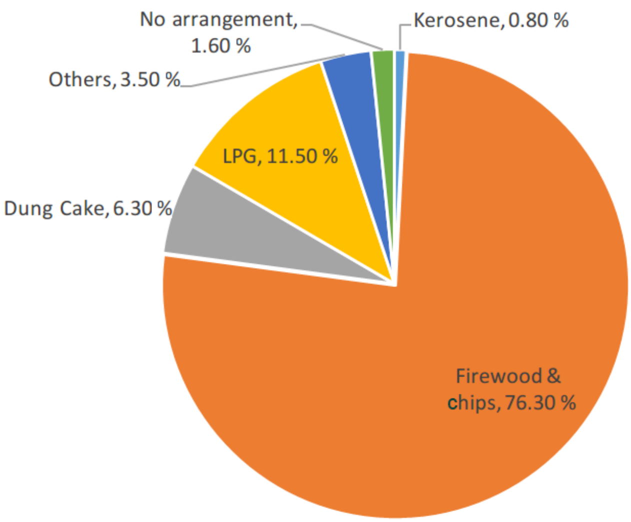

Figure 6. Energy sources used for cooking in rural India, 2009–2010.

3.4 Domestic fuel

The domestic fuel sector includes emissions from firewood, agricultural residue, coal, liquid petroleum gas (LPG), kerosene (cooking and lighting) and dung cake.

India faces a crucial challenge of providing clean and affordable energy sources to its rural households, especially in the cooking sector. Eighty-five percent of the rural households are still dependent upon traditional biomass fuel for their cooking needs (MoSPI, 2014b). Figure 6 shows the distribution of rural households on the basis of the energy source used for cooking (MoSPI, 2014b).

The stoves used for cooking are inefficient, causing incomplete combustion and hence releasing more BC than would result from efficient combustion. In the year 2000, domestic fuels contributed 64 % to the total BC emissions in Asia (Streets et al., 2003). State-wise per capita consumption (rural and urban) of firewood, LPG and coal was taken from a National Sample Survey (MoSPI, 2014b), which releases a report of household consumption of various commodities using a large sample of households every 5 years. Apart from this, Yevich (2003) report the state-wise total consumption of firewood, agriculture residue and dung cake in 1985. We extrapolated the fuel consumption data to 2011 by using the growth rate of rural population from 1985–1991 and the change in the number of households using these fuels for cooking from 1991 to 2011. Smith et al. (2000) also report the state-wise consumption of firewood, dung cake and agricultural residue in 1991. We extrapolated the data to 2011 using the change in number of households using these fuels for cooking from 1991 to 2011. Using data from MoSPI (2014b), Yevich (2003) and Smith et al. (2000), three estimates of domestic fuels consumed in 2011 were prepared and used within the uncertainty analysis.

According to the World Bank (2010), 25 % of the Indian population does not have access to electricity. As a result kerosene-fueled lamps are the only source of lighting after sunset for a large part of the population. In 2011, over a billion liters of kerosene was consumed to fuel these lamps (MoSPI, 2014b). The information on kerosene consumed was available from two sources: MoSPI (2014b) and Lam et al. (2012). The National Sample Survey (MoSPI, 2014b) reports the state-wise per capita (rural and urban) kerosene consumption. The proportion of kerosene used for cooking versus lighting in India was taken from Lam et al. (2012). Another estimate of kerosene consumed in lamps was derived following the methodology described in Lam et al. (2012).

3.5 Other

The sector "other" incorporates emissions from the use of diesel in power generation sets. One of the largest consumers of diesel are irrigation pumps. In addition, diesel is used in power generation for mobile towers, private households, small industry and commercial enterprises.

3.5.1 Irrigation pumps

Agriculture is a core economic activity of India, with about 60 % of the population involved in the activity. In 2011 India used around 2.4 billion liters of diesel for irrigation pumps (MoPNG, 2013). The use of dug wells and tube wells is very common for irrigation purposes in India. Diesel powered pumps are used for mini irrigation schemes in farms with minimal or no access to electricity. The diesel consumed was distributed district-wise according to the net sown area in that district (Ministry of Agriculture, 2011).

3.5.2 Diesel generator sets

In 2011–12, India faced an overall power deficit of 8.5 % and peak power shortage of 10.6 % (CEA-LGBR, 2013). To deal with this deficit, there were prolonged power cuts throughout the country especially during the peak consumption period. Increasingly, private households, commercial enterprises and industries are using diesel generators to maintain consistent power supply during power outages. Although there is no official estimate of the amount of diesel consumed by diesel generators, ICF International estimates that 4.51 billion liters of diesel was used in the year 2012–13 (Shakti Sustainable Energy Foundation, 2014). The growth rate of the power deficit in India was used to adjust this value for 2011 (CEA-LGBR, 2013). The telecom industry is one of the largest users of diesel generators. In 2011, India had more than half a million cell towers (Press Information Bureau, 2011). Most of these towers are located in villages where grid-connected electricity is not available. They use small generators fueled by diesel for their power needs. The total diesel consumption by cell towers was taken from MoPNG (2013). The fuel con-

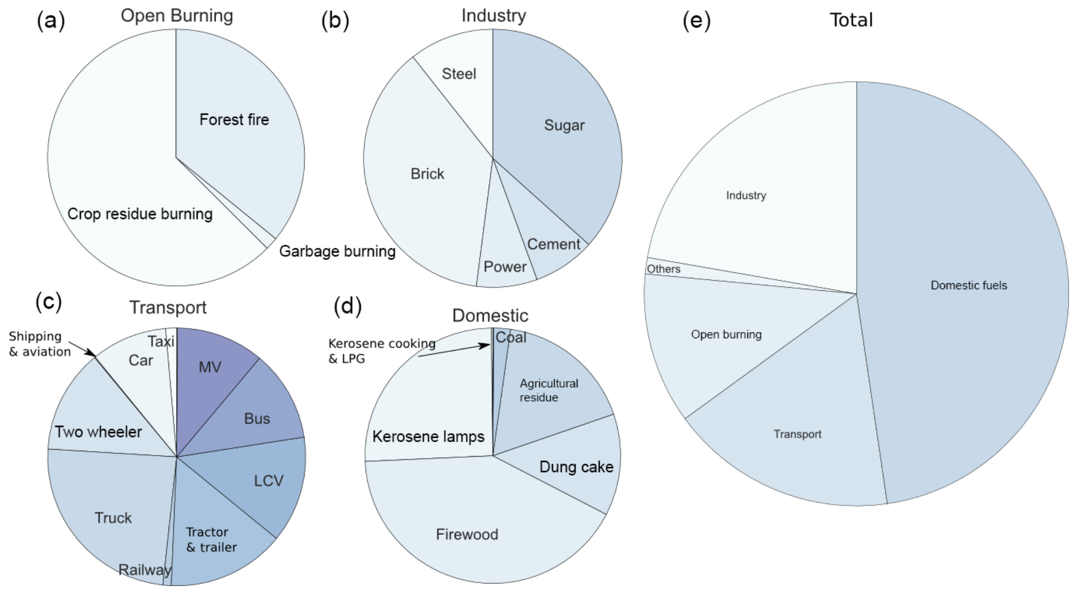

Figure 7. (a–d) Proportion of subcategories to the major sector emissions and **(e)** contribution of major sector emissions to the national emissions total.

sumed was distributed state-wise according to the number of mobile towers in that state. It was then distributed district-wise according to the population of the district. Diesel consumed by generators in mobile towers was deducted from the total amount of 4.51 billion liters consumed by diesel generators to estimate the remaining amount. Due to the paucity of data it was not possible to spatially distribute the remaining emissions to grids, so they have only been accounted for in the total national emissions.

4 Results and discussion

Tables 1 and 2 present the probabilistic best-fit distributions, mean and standard deviation for activity data and EFs for sources considered in this study. The mean district level activity data and EFs were used to estimate the district-wise emissions. It may be noted that kerosene lamps have the highest EF among all sources considered in this study; these lamps convert 8.5 % of the fuel directly into BC. In the open-burning sector, forest fires have the highest EF. In the industry sector, EF is highest for the sugar industry, as the industry uses bagasse as a fuel in a very inefficient combustion process. For the transport sector, EFs for diesel-operated vehicles (railways, ships, bus, truck, tractor and trailer, LCV) are higher than that for gasoline-operated vehicles (two wheeler, LMV, car).

Total BC emissions for the year 2011 have been estimated to be 901 ± 152 Gg (Table 3), of which 47 % (425 Gg) originated from domestic fuel consumption, 22 % (198 Gg) from industry, 17 % (154 Gg) from the transport sector and 12 % (103 Gg) from open burning. Diesel use in mobile towers and irrigation pumps contributed 2 % (20 Gg) to total BC emissions (Fig. 7). Firewood with emissions of 177 Gg is the single most emitting source. It emits more than transportation (154 Gg) and open-burning (103 Gg) categories. As shown in Fig. 6, 76.3 % of the 140 million rural households MoSPI (2014b) use firewood as the primary source of energy for cooking.

The spatial distribution of national emissions is presented in Fig. 8. From the map it can be easily concluded that the Indo-Gangetic Plain (IGP) is the main contributor to national BC emissions. This can be attributed to the very high population density and presence of major BC emitting industries like sugar and brick production in this region. Some of the states in the IGP are among the least developed in India, with little access to even basic amenities like electricity, clean cooking fuels, sanitation, health care, etc. More than 90 % of the rural households in Uttar Pradesh and Bihar use biomass fuels as their primary source of cooking, and more than 65 % are dependent upon kerosene lamps as their primary source of lighting (NSSO, 2015). The high dependence on biomass fuels and the presence of brick and sugar industry accentuates the emissions from this region. With annual emissions of 140 Gg, the state of Uttar Pradesh emits the most in the IGP followed by West Bengal (57.67 Gg), Bihar (47.8 Gg), Punjab (34.01 Gg), Haryana (26.82 Gg) and the National Capital Territory (NCT) of Delhi (6.74 Gg). The major emissions sources in Uttar Pradesh are kerosene lamps (12 %), biomass cooking fuels (30 %), brick kilns (20 %) and sugar mills (17 %). High emissions from IGP and its vicinity to the Himalayas potentially pose a serious threat to water security in the region, resulting from impacts on the cryosphere from BC deposition and atmospheric heating.

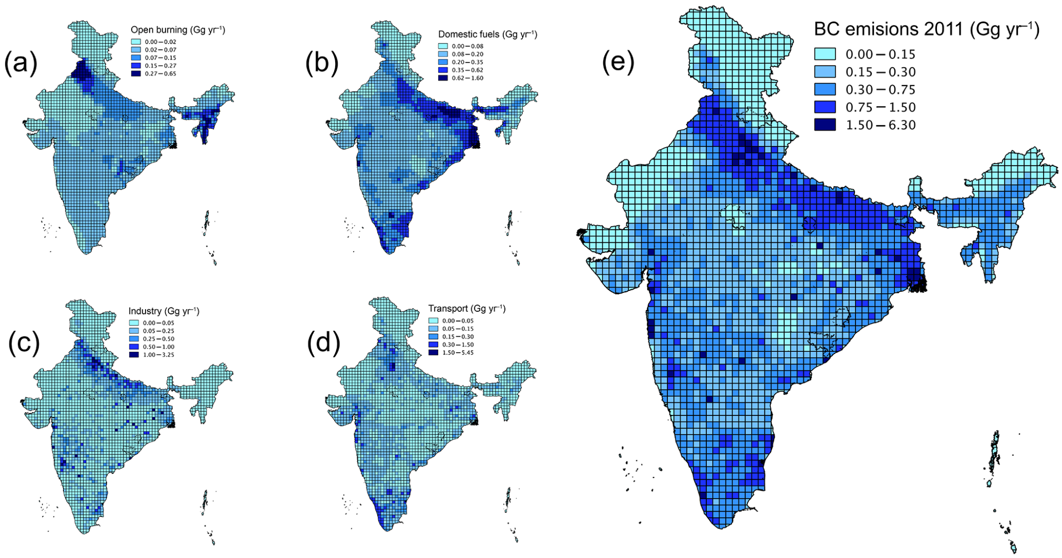

Figure 8. **(a–d)** Maps of major sector emissions and **(e)** spatial variability of national emissions total for BC.

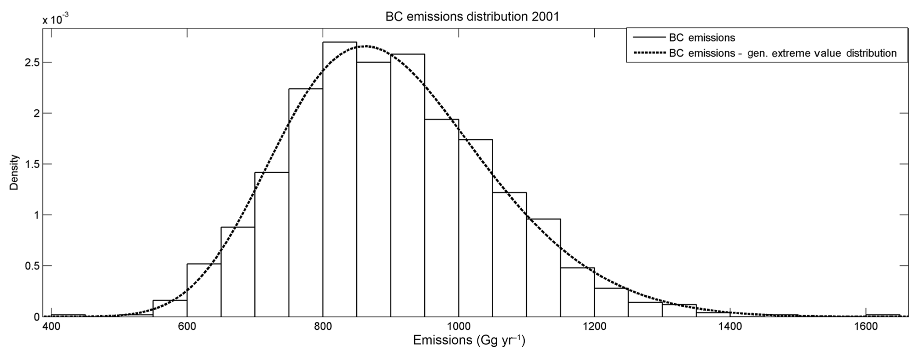

Figure 9. Gen. extreme value distribution fit for the national BC emissions.

As discussed in Sect. 2, best-fit probabilistic distributions were obtained for EF and activity data (for each source) using the KS statistic. A sample of 1000 numbers was generated from each of the two distributions (EF and activity data), the product of which provides over 1 million emission points. The mean and standard deviation were determined for each source using the obtained emission points. The emission points were added up for all the sources to get, overall, 1000 national emission points and, subsequently, the national mean emission and standard deviation. A best-fit probabilistic distribution curve was obtained for the national emission points on the basis of the KS statistic. The probabilistic distribution for overall national emissions was found to be a general extreme value distribution with KS statistics of 0.01 (Fig. 9). Figure 10 presents the sector-wise optimally fit distributions for the BC emissions.

4.1 Open burning

The national level emissions from this sector contribute 12 % (103 Gg) to the total emissions. Burning of crop residue has been the major contributor (62 %), followed by forest fires (36 %). MSW burning contributed only 2 % to the open-burning emissions. The source-wise emission contribution and spatially distributed open-burning emissions are presented in Figs. 7 and 8. The emissions from open burning are highest from the northwest states of Punjab and Haryana (crop residue burning) and the northeastern states of Nagaland, Manipur, Mizoram and Tripura (forest fires). Punjab and Haryana are the main food-producing states of India. In April, May, October and November, the crop residue is burnt to clear the land for the next crop. In the northeast, open-burning emissions arise primarily from forest fires; however, some tribal communities also practice slash and burn agriculture in this region as well.

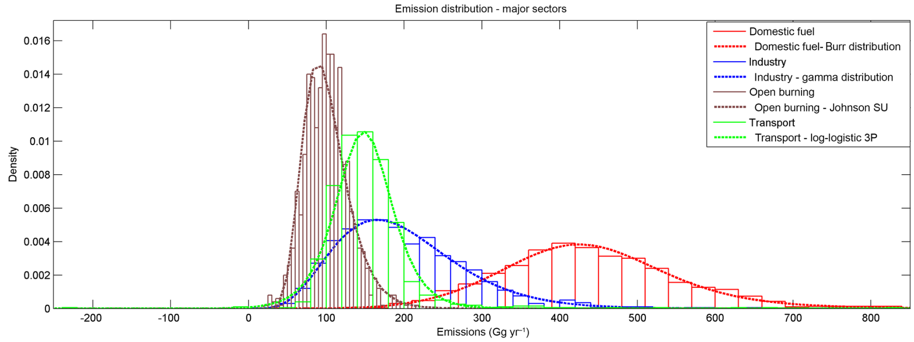

Figure 10. Sectorial emission histograms and associated best-fit PDFs.

4.2 Industry

National level industry sector emissions account for 22 % (198 Gg) of the total emissions. In this sector, brick and sugar production contribute the maximum emissions (37 % each), followed by steel production (11 %), cement (8 %) and powerplants (7 %) (Fig. 7). Spatially distributed emissions from the industry sector are presented in Fig. 8. The hotspots of industrial emissions are the states in the IGP, as most of the brick and sugar industries lie in this area. It is also evident and expected from Fig. 8 that metropolitan cities contribute significantly to the sector as they have major industrial belts on the periphery. High emissions from the brick and sugar industry result from the use of low-grade fuels and from dated and inefficient systems and processes. While powerplants account for 75 % of coal consumption, their BC emissions are just 7 % of the total industrial emissions, due to the higher efficiency of combustion in these systems. An acknowledged source of uncertainty in our approach is the lack of specific geolocated coordinate data for the two largest emission sources, brick and sugar.

4.3 Transport

Transportation sector emissions account for 17 % (154 Gg) of the national BC emissions in 2011. In the transport sector trucks have been found to emit the most (24 %), followed by tractor and trailers (15 %). Emissions from bus, car, LCV, LMV and two wheelers contributed 12, 10, 13, 11 and 13 % to national transport sector BC emissions, respectively. Railways contributed 0.2 % to BC emissions in 2011; shipping and aviation combined emitted less than 0.05 % (Fig. 7). The spatial distribution of transportation emissions is presented in Fig. 8. The main contributors are the metropolitan cities, the NCT of Delhi, Mumbai and Bangalore. The results also indicated that the majority of the emissions from the transport sector originate from diesel road vehicles (truck, tractors and trailers, bus, LCV and LMV).

4.4 Domestic fuel

Domestic fuels account for almost half of the national BC emissions (47 %, 425 Gg). Within the sector, firewood contributes most significantly, (42 %), followed by kerosene lamps (26 %). Agricultural residue, dung cake and coal used for cooking contributed 17, 13 and 2 %, respectively (Fig. 7). Figure 8 shows the spatially distributed emissions of domestic fuel usage. Here also, the majority of emissions arise from the IGP due to the high population density in this area. Also, the poverty levels are high in this region, so a larger proportion of the population tends to use cheaper biofuels for cooking. The biofuel used in handmade stoves has low combustion temperatures leading to an inefficient combustion process, and consequently the domestic fuel sector has higher BC emissions. Also, these are uncontrolled emission sources. Kerosene lamps (109 Gg) are the second-highest emitting source as a result of the very high EF of kerosene lamps. While the emissions from kerosene lamps are more than the entire open-burning sector combined, studies must be conducted to evaluate the potential impact and transport of this source of BC. It likely has extremely significant health impacts due to the emissions being contained within homes, but the climate impact is likely as large as for open burning.

4.5 Other

Emissions from this category account for slightly more than 2 % (20 Gg) of the national BC emissions. Within this category emissions from use of diesel in irrigation pumps contribute 8 Gg, and its use in mobile generators contributes 12 Gg. Among diesel generators, their use in mobile towers contributes 4 Gg and other applications (private households, small commercial enterprises and industry) account for the remaining 8 Gg.

4.6 Uncertainty analysis

Figure 11 shows the mean and standard deviations based on best-fit probabilistic distributions of emissions from the major sectors. Based on the Monte Carlo simulations using the

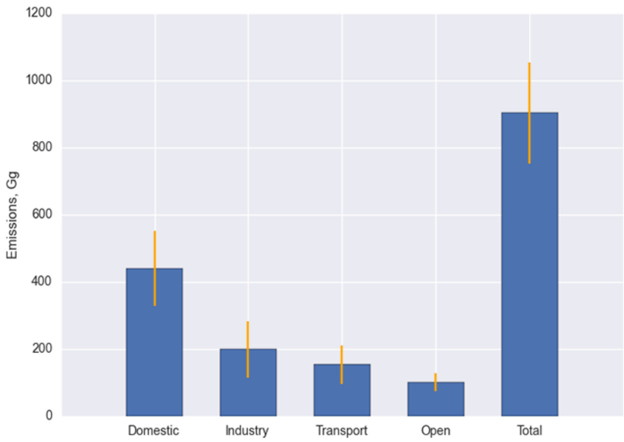

Figure 11. Mean and standard deviation for each of the major sectors of emissions for India, 2011.

multiple emissions estimates and available information on uncertainty, the PDFs for each of the sectors is calculated as shown in Fig. 10. The best-fit distribution for the domestic fuels sector was found to be a Burr distribution with a KS statistic of 0.01; for industrial emissions, it was a gamma distribution with KS statistics of 0.02; for open-burning emissions, it was a Johnson SU distribution with a KS statistic of 0.02; and it was log-logistic (3P) for the transport sector, with a KS statistic of 0.03. The uncertainty is highest for emissions from the domestic fuels sector. The EFs and activity data for the sources in the domestic fuel sector show a large variation leading to high uncertainty in the BC emissions as there is no accurate database of the population using cookstoves, of the quantity of fuel consumed and the stoves' efficiency.

4.7 Comparison with prior estimates

Emissions in this study have been determined using a Monte Carlo simulation of multiple activity data and emission factors. As previous studies have used point estimates for these highly uncertain quantities, the results are bound to differ. Figure 12 presents the comparison of the results of this study (Table 3) with emission inventories developed in the past. For the base year 2011, the estimate is about 80 % of that reported in the SAFAR emission inventory (1119 Gg yr^{-1}). For inventories with base year 2010, total national emissions estimated in this study are a factor of 1.3 higher than RETRO (697 Gg yr^{-1}), factor of 0.8 of that estimated in Klimont et al. (2009) (1104 Gg yr^{-1}), a factor of 0.9 of that estimated in Lu et al. (2011) (1015 Gg yr^{-1}), and they were in agreement with emissions determined by Ohara et al. (2007) (862 Gg yr^{-1}). All prior national emission estimates lie within 2 standard deviations of our mean estimate.

Emissions estimates from the domestic fuels sector (425 ± 112 Gg yr^{-1}) are lower by a factor of 0.7–0.9 than Pandey et al. (2014) (488 Gg yr^{-1}), Klimont et al. (2009) (628 Gg yr^{-1}) and Lu et al. (2011) (579 Gg yr^{-1}). For the transport sector our emission estimate (154 ± 56 Gg yr^{-1}) is almost identical to that presented in Sadavarte and Venkataraman (2014) (144 Gg yr^{-1}) and a factor of 1.1–1.3 higher than the emissions determined by Lu et al. (2011) (111 Gg yr^{-1}), Baidya and Borken-Kleefeld (2009) (123 Gg yr^{-1}) and Klimont et al. (2009) (136 Gg yr^{-1}). In the industry sector our emissions (198 ± 83 Gg) are 10–20 % lower in view of the inclusion of only higher emitting industries in this study. The combined industrial emission estimate of Sadavarte and Venkataraman (2014) (formal industry) and Pandey et al. (2014) (informal industry) (212 Gg yr^{-1}) is in

Table 3. Mean national emissions and standard deviation.

Sector/subsector	Emissions (Gg yr^{-1})
Open burning	102.84 ± 27.56
Crop residue burning	64.31 ± 17.19
Forest fire	36.90 ± 12.85
Garbage burning	1.63 ± 0.62
Industry	198.5 ± 83.391
Brick	74.11 ± 61.38
Steel	21.09 ± 32.18
Sugar	72.76 ± 25.05
Cement	15.45 ± 22.26
Power	15.09 ± 23.88
Transport	154.34 ± 56.14
Bus	17.64 ± 8.72
Car	14.69 ± 10.54
LMV	17.01 ± 25.03
LCV	20.62 ± 10.51
Truck	37.46 ± 20.49
Taxi	2.13 ± 1.44
Two wheeler	20.11 ± 39.50
Tractor and trailer	22.79 ± 11.41
Railway	1.60 ± 1.32
Shipping	0.15 ± 0.07
Aviation	0.14 ± 0.04
Domestic fuel	425.36 ± 111.97
Dung cake	54.79 ± 48.15
Agriculture residue	74.38 ± 44.17
Firewood	177.34 ± 83.88
Coal	9.02 ± 14.622
Kerosene cooking	0.83 ± 0.19352
LPG	0.47 ± 0.39
Kerosene lamps	108.53 ± 27.10
Others	20.08 ± 2.59
Irrigation pumps	7.55 ± 1.73
Diesel generators (mobile towers)	4.14 ± 0.85
Diesel generators (other)	8.39 ± 1.73
Total	901.11 ± 151.56

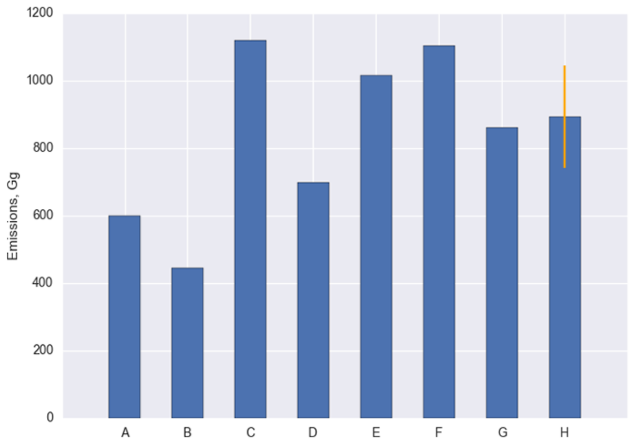

Figure 12. Comparison of current BC emissions estimate with previously published results for India. A: Streets et al. (2003) (base year 2000); B: Reddy and Venkataraman (2002a, 2002b) (base year 1997); C: Sahu et al. (2008) (base year 2011); D: Schultz et al. (2008) (base year 2010); E: Lu et al. (2011) (base year 2010); F: Klimont et al. (2009) (base year 2010); G: Ohara et al. (2007) (base year 2010); H: this study (base year 2011).

good agreement with our emission estimate (factor 0.94). Estimated industrial emissions are a factor of 0.8–0.9 lower than Lu et al. (2011) (227 Gg yr^{-1}) and Klimont et al. (2009) (261 Gg yr^{-1}). Emissions from open crop residue burning (64 ± 17 Gg yr^{-1}) are in close agreement (factor 0.8–1) with Jain (2014) (68 Gg yr^{-1}), Lu et al. (2011) (74 Gg yr^{-1}) and Pandey et al. (2014) (80 Gg yr^{-1}). Forest fire emissions (37 ± 13 Gg) are almost identical to those determined in Reddy and Venkataraman (2002a) (39 Gg yr^{-1}). As with the national emission estimate, for all sectors prior emission estimates are within 1 or 2 standard deviations from our mean emission estimate.

4.8 Fuel balance

A fuel balance approach has been used to ensure that no major emission source has been overlooked in our study. Since biomass consumption data in India are highly uncertain, this approach was only employed for emissions arising from combustion of fossil fuels. Emissions from combustion of diesel, gasoline, fuel oil, ATF, LDO and coal were estimated using emission factors from Streets et al. (2003) and Bond et al. (2004). In 2011, emission from these fuels was estimated to be 281 Gg (Table 4). This was very close to emissions estimated from our methodology (304 Gg), considering the emission sources which use these fuels as a combustion source.

4.9 Seasonality of emissions

There is a strong seasonality associated with BC emissions in India. Crop residue burning, forest fires, and the brick and sugar industry have a seasonal dependence in emissions. Forest fires are predominant from February to July. Monthly BC emissions from forest fires were estimated using MODIS burnt-area data. The brick industry becomes active after the monsoon season from October to June (Maithel et al., 2012); the sugar industry operates from November to June (Tyagi, 1995), and the emissions are equally distributed among the months of operation. Burning of crop residues generally occurs in the harvesting months, which are October–November for kharif crop and April–May for rabi crop. Emissions of agricultural open burning are equally distributed among the months of April, May, October and November. For all the other sources, emission rates are assumed to be uniform throughout the year. Using these data, monthly variation of BC emissions has been estimated and is shown in Fig. 13.

The emissions in April are highest due to the burning of crop residues. Despite the absence of crop residue burning, emissions in March are also high because of the emissions from forest fires. As we have shown that a considerable amount of the emissions comes from the IGP, which is in close proximity to the Himalayas, this causes further concern regarding the potential cryospheric impact of these aerosols as they are strongest during the period when the seasonal snowmelt period is beginning and they could be incorporated into the snowpack.

Table 4. Fuel balance.

Sector/fuel	Activity (Mt)	EF (g kg^{-1})	Emission (Gg)
Coal	535.88[1]	0.328[2]	175.77
Gasoline/petrol	14.442[3]	2.795[4]	40.37
Diesel	63.504[3]	1.02[4]	64.77
Fuel oil	6.624[3]	0.04[4]	0.26
ATF	5.324[3]	0.03[4]	0.16
Total			281.33

[1] MoSPI (2014a). [2] Streets et al. (2003). [3] MoPNG (2014). [4] Bond et al. (2004).

5 Conclusions

A spatially resolved BC emission inventory for 2011 has been developed, considering major sectors and with careful consideration of subsector sources. The sources were classified into five major sectors: (i) open burning, including forest fire emissions, open solid-waste burning and agriculture residue burning; (ii) industry, including brick industry, cement, steel plants, sugar mills and powerplants; (iii) transport, including two wheelers, cars, light motor vehicles passenger, light commercial vehicles, taxies, trucks, buses, tractors and trailers, railways, shipping, and airways; (iv) domestic fuel, including firewood burning, agricultural residue, coal, liquid petroleum gas, kerosene (cooking and lighting)

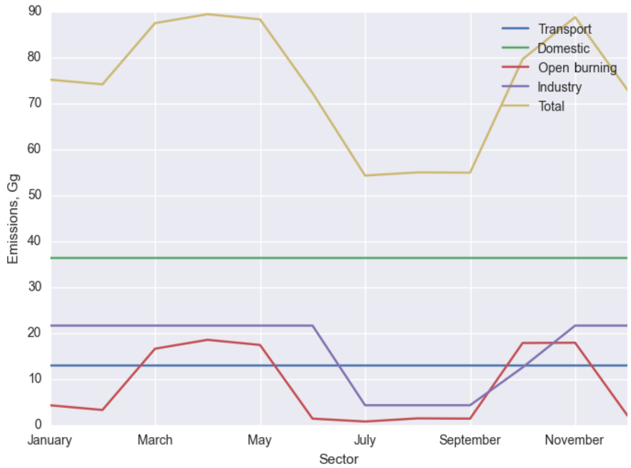

Figure 13. Time series of monthly emissions for India, 2011. Note the strong seasonality of the open-burning and industry sector. In the latter case, the seasonality results predominately from sugarcane production.

and dung cake; and (v) "other", including use of diesel in irrigation pumps and for other power generation in diesel generators.

This is a first-of-its-kind comprehensive study which included sources such as kerosene lamps and forest fires that were not part of earlier emission inventories. Furthermore, for each sector, source uncertainties in emissions have been estimated based on variability in available activity data and emission factors. Lastly, and significantly, we provide our estimate of emissions at a monthly temporal resolution on a spatially distributed 40 × 40 km. grid.

The national BC emissions for India in 2011 are estimated to be $901 \pm 152\,\mathrm{Gg\,yr^{-1}}$, with domestic fuels contributing the most (47 %), followed by industries (22 %), transport (17 %), open burning (12 %) and others (2 %). Large emission in the domestic fuels sector stems from the extensive use of biomass for cooking in India. Firewood is the single largest emitter, with 177 Gg (20 %) of BC emissions in 2011. The emissions from firewood are more than the entire transportation sector combined. Kerosene lamps surprisingly contribute 12 % to the national BC emissions. The emissions have been found to be have a significant seasonality, varying from 55 Gg in July to 90 Gg in April 2011.

The results of the study could be used to assess the contribution of different sources to national and regional emissions. The spatial resolution of the inventory should be useful for modeling the black carbon processes in the atmosphere through air quality models. Monthly gridded emission data sets can also be prepared for finer temporal-resolution input. To improve the future BC emission estimates, local emission factors and activity data should be improved, especially for domestic fuels and the brick industry. The emission inventory can be improved nationally, regionally and temporally by comparing the modeled emission estimates (providing the inventory as input to air quality models) with the observed data.

6 Data availability

The inventory is available from the authors on request. More information may be found at http://www.mn.uio.no/geo/english/research/projects/hycamp.

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