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Decadal growth of black carbon emissions in India

S. K. Sahu,[1] G. Beig,[1] and C. Sharma[2]

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[1] A Geographical Information System (GIS) based methodology has been used to construct the black carbon (BC) emission inventory for the Indian geographical region. The distribution of emissions from a broader level to a spatial resolution of 1° × 1° grid has been carried out by considering micro level details and activity data of fossil fuels and bio-fuels. Our calculated total BC emissions were 1343.78 Gg and 835.50 Gg for the base years 2001 and 1991 respectively with a decadal growth of around 61%, which is highly significant. The district level analysis shows a diverse spatial distribution with the top 10% emitting districts contributing nearly 50% of total BC emission. Coal contributes more than 50% of total BC emission. All the metropolitan cities show high BC emissions due to high population density giving rise to high vehicular emissions and more demand of energy. **Citation:** Sahu, S. K., G. Beig, and C. Sharma (2008), Decadal growth of black carbon emissions in India, *Geophys. Res. Lett.*, *35*, L02807, doi:10.1029/2007GL032333.

1. Introduction

[2] The dark component of carbonaceous aerosols often referred to as soot or BC. The BC absorbs near UV, visible and near IR region of electromagnetic radiation strongly, due to its unique graphitic micro crystal like structure. All combustion processes release BC as byproduct. Energy related emission of BC, on the global scale, fossil fuels and bio-fuels account 66% and 34% respectively [*Reddy and Boucher*, 2007]. In this global emission budget, East and South Asia contribute to more than 50%. However, the work related to estimates of the emissions of black carbon and especially its growth over the years in a developing country like India is in initial stage. *Cooke et al.* [1999] have constructed the global-scale gridded fossil fuel emission inventory of carbonaceous aerosols and calculated the radiative impact. However, if one applies it for a smaller domain like India then we finds that lot of assumptions are made in the absence of micro level details of activity data. Recently, *Venkataraman et al.* [2005] have estimated the BC emissions from bio-fuel combustion. They also suggested that its control is the central to climate change mitigation in the South Asian region. *Bond et al.* [2004] have reported a technological-based inventory of BC emissions from combustion.

[3] The use of GIS in developing emission inventory is at emerging stage in India. Earlier *Dalvi et al.* [2006] have used the GIS tool to grid the emissions of carbon monoxide (CO). *Streets et al.* [2003] and *Cao et al.* [2006] have used GIS for gridding emissions for several gases. Emission in gridded form is always required as input to exercise the atmospheric models. It is very important that these emissions should correctly reflect the spatial and temporal emission profile of sources which is often not available in particular for Indian geographical region. So far, the growth of BC emissions over the past years has not been reported for the Indian region, which is emerging as the strong economic power in South Asia as well as in the World. Such studies need to be conducted to understand the extent of additional radiative forcing emerging due to the growth of BC emissions. In this paper, the gridded BC emission inventories for Indian geographical region has been developed in the spatial resolution of 1° × 1° and its decadal growth during 1990s have been studied in a compressive and consistent way. For the purpose, we used the GIS based statistical methodology based on various micro details of activity data of all major anthropogenic sources, such as fossil fuels and bio-fuels.

2. Methodology

[4] Coal, petrol, and diesel are considered as major energy sources under the fossil fuel category (e.g., thermal power station, steel plants, cement plants and transportation sector) whereas cattle manure, fuel wood and agricultural residues burning are the main energy source considered under the bio-fuel category in the present study. As most of the basic data used are at national and state levels, where the requisite state and district level data are not available, we computed state and district level data from national level data using appropriate socio-economic statistics such as urban / rural population, area, decadal population growth, industrial output, vehicle registration numbers etc. Further, these emission sources are of two categories, namely large point source (LPS) and area sources. In LPS category, we have included emissions from thermal power plants, steel plants and cement plants for this inventory estimation with their location information. We have accounted around 185 LPSs (84 thermal power plants, 12 steel plants and 87 cement plants) for the year 2001 and 170 LPSs (71 thermal power plants, 12 steel plants and 87 cement plants) for the year 1991. During last decade (1991–2001), the capacities of production of various existing plants have increased significantly rather than establishing new plants in some other places. So the increase in number of LPSs is very small. The LPSs consume more than 95% of total coal used in industrial sector. Less than 5% is used in small scale industries like bakery industries, brick industry, industrial processing etc. In some past work, the district-wise emission values are assigned to corresponding district headquarters for each source as point data source [*Dalvi et al.*, 2006]. But representing district as polygon would give better

[1]Indian Institute of Tropical Meteorology, Pune, India.
[2]National Physical Laboratory, New Delhi, India.

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Table 1. Comparison of the Emission Factors for BC Emissions as Reported by Different Authors

Fuel-Type	*Cooke et al.* [1999]	*Venkataraman et al.* [2005], Center Value	*Bond et al.* [2004]	*Dickerson et al.* [2002]	*Reddy and Venkataraman* [2002]	*Streets et al.* [2003]
Coal	2.13[a] [Undeveloped] 1.22 [semi-developed] 0.75 [developed]	———	0.000–0.002	Power Plant [0.0001] Industrial Coal [0.32]	1	Coal consumption in Industries [0.056–0.6]Domestic Sector [0.12–3.7]
Diesel	10[a] [Undeveloped] 10 [Semi-undeveloped] 2 [developed]	——––	Residential [0.06–4] Industry [3.4–4.4]	12	0.7	
Bio-fuel	—–	Fire Wood [0.50][a] Dung [0.85][a] Agri-Residue [0.145][a]	Fire Wood [0.85] Dung [0.53] Agri-Residue [1]	Residential Biofuel [1]	Fire Wood [0.28] Dung [0.328] Agri-Residue [0.446]	1
Petrol	0.15[a]			0.23		
Kerosene	0.03[a]		0.9		0.3	

[a]Emission Factor (EF in g/kg) used in current work.

representation and will be more ideal which is used in the present work. The industrial sources (LPS) were considered as area sources rather than point sources and their emission estimation was assigned to corresponding district in which they are located because, out of 588 districts, 536 districts (91%) have area less than $1^\circ \times 1^\circ$ area and only 52 districts (9%) have area more than $1^\circ \times 1^\circ$ area So we have considered the LPS as area source. In less developed countries, control of emission are not such a high priority where as in developed counties the emission sources are replaced by more efficient modern technologies for reduced emissions [*Cooke et al.*, 1999]. It is seen that for industrial usage in developing and underdeveloped counties, the emission factor (EF) is 5 times of that of developed counties [*Etemad and Luciani*, 1991]. *Kandlikar and Ramachandran* [2000] noticed that diesel vehicles in less developing counties (industrializing counties) such as India and probably China produce 17 times more particulate matter per mile than in the USA. BC emissions from different sources are mainly dependent upon the technology used and detailed country-specific technology-wise BC emission factors from most of the sector are not yet available in India. *Venkataraman et al.* [2005] has developed the EF for bio-fuel (fuel-wood, cattle manure and corp waste) for Indian conditions which is probably more representative for Indian region. Hence, in the current work, the emission factors for bio-fuel usages are taken from *Venkataraman et al.* [2005]. *Cooke et al.* [1999] has categorized the EF for different fossil fuels based on the combustion technologies used in underdeveloped, semi developed and developed countries. The emission factors provided by *Cooke et al.* [1999] for different kinds of fossil fuel for underdeveloped countries have been used for generating national level BC estimates. We have used *Cooke et al.* [1999] values of EFs for all the sector except that of bio-fuel because we, in our expert judgment, feel that these gross values are more representative for a suite of technologies used in different sectors consuming specific fuels like coal, diesel, petrol etc in India in view of non-availability of technology-specific emission factors. A comparison of the emissions factors as reported by different workers are tabulated in Table 1.

[5] Activity data were collected from different government websites: Central Electricity Authority (CEA), Monthly generation report of different power plants, 2003, available at www.cea.nic.in; Census of India, Indian 2001 census data, 2001, available at http://www.censusindia.gov.in/2001; Ministry of Coal (MOC), Annual report year 2001–2002, 2002, available at http://coal.nic.in/content0102.htm; Ministry of Road Transport and Highways (MRTH), Total registered motor vehicles in India from 1998 to 2004, 2004, available at http://www.morth.nic.in/writereaddata/sublinkimages/table-2880444301.htm; and Ministry of Agriculture (MOA), Report of the Committee on Capital Formation in Agriculture, 2004, available at http://agricoop.nic.in/statatglance2003.htm; Second advance estimates of foodgrains production for 2003–04, 2004, available at http://agricoop.nic.in/Capital%20Formation/aeof2003-04.htm. Quantifying BC emission is more challenging task than any other atmospheric pollutants emission. There are large uncertainties in the source strength of carbonaceous aerosols [*Cooke et al.*, 1999; *Intergovernmental Panel on Climate Change*, 2001]. The activity data related to consumption of fossil fuel at national level used in present calculations have nearly negligible uncertainties.

[6] A raster base map of India showing political boundaries has been procured from Survey of India (SOI) and geo-referenced using Ground Control Point (GCP), digitization of the national, state and district boundaries in the form of polygons were carried out using GIS tools. For the gridding, a geo-referenced grid box of $1^\circ \times 1^\circ$ covering Indian Geographical area was prepared using GIS tool. In the current work, we have taken 588 districts and union territory regions and 408 grid cells of $1^\circ \times 1^\circ$ covering the Indian geographical region. The district-wise emission values for each source have been mapped as area source rather than point source. Only national level and in some cases, state level inventory are available for the Indian region for the base years 2001 and 1991. So using GIS based statistical methodology, we have down scaled the national level inventory to state level inventory and again down scaled the state level to district level using local micro-level details and active data (rural/urban population, vehicle number data, coal used data, bio-fuel data and agricultural production) discussed in the next section. The prepared grid cells layer was superimposed over the district level-mapped layer to extract the gridded value for Indian region. The emission

Table 2. Capacity and Consumption of Coal in Different Industries With Weightage

Industry	Capacity, tonnes per annum	Annual Coal Requirement, tonnes
Power Plants	250 MW	1350000
Steel plants	500000 tpa	300000
Cement plants	500000 tpa	100000

values for the gridded cells were calculated based on the corresponding district's contribution from different sources lying inside the grid cells. Similarly, the emission values are computed for all grids over the Indian geographical region. The emission values from different sources are also organized as set of thematic layers so that they can be analyzed separately.

3. Preparation of Database

[7] The major consumers of coal in India are the thermal power stations, followed by the steel plants and cement plants. Coal production in India was around 212 MT and 333 MT for the year 1991 and 2001 respectively (MOC, http://coal.nic.in/content0102.htm). Major big plants consume about 81% of coal and rest 19% is used by other sources (residential, commercial and small industrial units) [*Dalvi et al.*, 2006], which are not available at district level as well as state level. As per capacity and consumption of coal as fuel, the plants units are assigned equal weightage to each category (1 steel plant = 3 cement plant = 0.22 power plant), tabulated in Table 2. The rest 19% coal is distributed to district level population as per capita consumption. In the current inventory studies, some uncertainties may occur due to inclusions of only major industries but it may be considered negligible.

[8] Nearly 70% of electric energy demand is met by the thermal power stations in India. The steel production also has increased from 15.1 MT in 1991 to 29.0 MT in 2001 (International Labour Organization, Steel in India SAIL's integrated plants, 1991, available at http://www.ilo.org/public/english/dialogue/sector/papers/stlmilln/chap3a.htm; Press Information Bureau (PIB), Steel, 2001, available at http://pib.nic.in/archieve/ppinti/milestones2002/milestones_02_steel.html). The total production of cement in all cement plants was 48.9 MT of which, large plants produced 45.75 MT and small plants produced only 3.15 MT. Total cement production has increased to 100.35 MT in 2001, which is an increase of 105% as compared to 1991 Indiastat.com, Plant-wise cement production capacity for the year 2001 and 1991, 2006, available at http://indiastat.com).

[9] Petrol and diesel are mainly consumed in transport sector in India, hence BC emission from petrol and diesel are related to vehicular population. Approximately 21.5 MT of diesel was used in 1991 which increased to 46 MT in 2001 (http://www.adb.org/Publications/year.asp). State level registered vehicles data is used in the absence of district level data (MRTH, http://www.morth.nic.in/writereaddata/sublinkimages/table-2880444301.htm). Data shows that there were nearly 55 millions and 21 millions registered vehicles in India for the years 2001 and 1991 respectively. We can see the growth in diesel consumption in respect to growth in vehicle numbers. In India, it is normally seen that vehicle population is directly proportional to urban population [*Pucher et al.*, 2005]. This is also because of the higher preference for personalized modes of transport due to unavailability of adequate mass transport systems. Based on the total number of vehicles in state and urban population of the corresponding state, per capita urban vehicle number is determined and urban population is used to estimate the district wise BC emission assuming that the vehicle number is directly related to the urban population. Due to absence of vehicular number data for the year 1991, national level data is used to generate district and state level vehicular number data. The national level data is used and it is allocated as per state/district level population for the year 1991. Still some uncertainty (2∼5%) might have been introduced due to ignoring small industries, which use petrol/diesel, not using the in-used vehicle numbers and relating the vehicle number with urban population. The biofuel burning data are classified into 3 different major categories viz. wood burning, cattle manure and agricultural residue burning. The wood and dung mostly burned to cook the food in rural areas and hence it has been allocated on the basis of rural population. After harvesting, the stalks of crops are left in the field and later it is burnt. The state level data from agriculture statistics 2001 and 1991 (Department of Agriculture and Cooperation, MOA, http://agricoop.nic.in/statatglance2003.htm) has been used for yield of all the different crops in the present work. Kerosene is generally used in rural area so consumed fuel is allocated based on the rural population of the districts (Census of India, http://www.censusindia.gov.in/2001).

4. Result and Discussion

[10] (Figures 1 top and 1 middle) shows the total BC emissions from all sources accounted in this analysis in gridded form for base year 1991 and 2001 respectively. The estimated BC emission for India from all sources is around 835.50 Gg for 1991, which increased to 1343.78 Gg in 2001. The grid-wise decadal change/growth in BC emission is shown in Figure 1 (bottom), which indicates a growth of around 61% (508.28 Gg) during 1990s. Maximum change occurred over Indo-Gangatic Plan (IGP) area (marked in red in Figure 1, top) and some parts of Western India and Southern India. The above given regions are having high population density as compared to other part of India. In the gridded image, the IGP belt shows more emission due to high population density and it is the most fertile region for agriculture in the country. Some parts of central India, North-western, Eastern, and Northeast region show less BC emissions as compared to other parts of India due to low population densities and few numbers of low capacity thermal power stations. All the metropolitan cities like Delhi, Mumbai, Kolkata and Chennai show high BC values due to high vehicular BC emissions and more demand of energy. The district level analysis shows that only top 10% emitting districts contributing nearly 49% and 52% of total BC emissions for the year 2001 and 1991 respectively. Out of 407 grid boxes, around 250 grids shows only change of BC less than 1 Gg which cover most parts of central India, North-east region and some parts of North-west region. All grid boxes showing higher values lie over

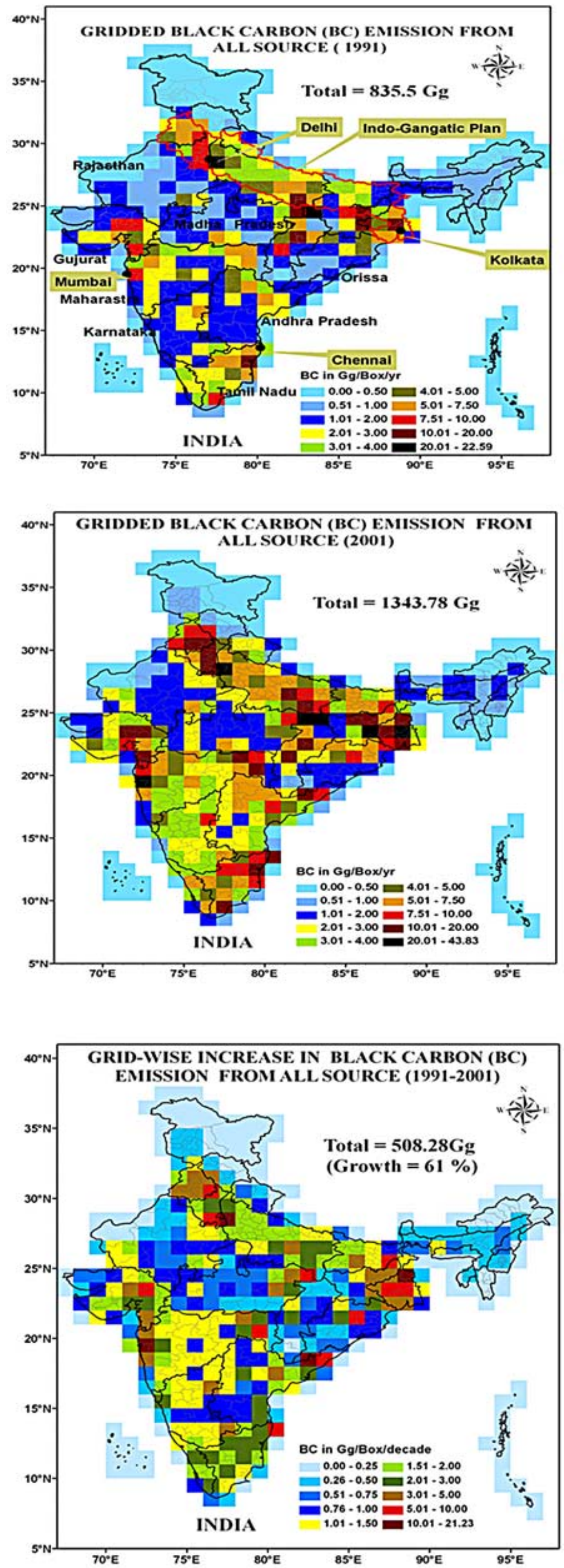

Figure 1. Gridded black carbon emission from all sources for the year (top) 1991 and (middle) 2001. (bottom) Variation in black carbon emission (in Gg) from all sources from 1991 to 2001.

some of the big cities of India. Most of grids showing values greater than 5 Gg is due to presence of high capacity thermal power station and high vehicular densities, which can be noticed in all the given figures.

[11] The sector-wise distribution and decadal growth is discussed in the following. Present calculation shows that the estimated BC emission from coal source is around 451 Gg for 1991 and around 709 Gg for the year 2001 with a decadal change of 57%. India is producing and consuming large amounts of coal. The coal consumption has increased by around 57% during 1991 to 2001 due to demand of coal by thermal power stations to generate electricity and by other industries also. Even though the coal consumption has increased by 57%, the power production is increased by around 85% (271 BUs in 1991 to 499.5 BUs in 2001) due to increase in efficiency of Plant Load Factor (PLF) which is an important metric of the operational efficiency of thermal power plants. IGP region is one of the most polluted area by BC due to high population density and 19% of total coal consumption is used by domestic sides. Decadal growth in BC is high over the IGP, Eastern parts of Southern India, Western India. Diesel and petrol are the major fuels consumed by transport sector in India. The estimated BC emissions from petrol and diesel source are around 218 Gg and 462 Gg for the year 1991 and 2001 respectively with 112% decadal growth due to rapid increase in vehicle number especially in urban areas. High values of BC from these sources are seen in the metropolitan cities like Delhi, Mumbai, Chennai, Kolkata and some districts of Western and South-eastern India. Vehicles using diesel emit more BC than vehicle using petrol. The BC emission over Indian region from bio-fuel source was estimated to be 166 Gg for the year 1991 and 172 Gg for year 2001 respectively with a decadal growth of 3.7%. Most of the bio-fuel related BC emission zones are located near major river belts and well-irrigated land as crop residue burning directly linked with more agriculture yields. The contribution of kerosene is negligible as compared to other fossil fuels. Kerosene is generally used in rural sector.

[12] A number of global BC emission estimates are available [*Penner et al.*, 1993; *Cooke et al.*, 1999; *Bond et al.*, 2004; *Dickerson et al.*, 2002] which also provides estimates for Indian subcontinent using emission factors developed mostly for the developed countries. Specifically for India, only few BC emission estimates from bio-fuel is available using EF for Indian condition [*Venkataraman et al.*, 2005]. *Cooke et al.* [1999] have estimated BC emissions of about 950 Gg/yr for rest of the Asia region (excluding China). *Streets et al.* [2003] have estimated 2540 Gg/yr BC for Asian region for the year 2000 which include estimated Chinese BC emissions of about 1005 Gg/yr. For India, *Venkataraman et al.* [2005] has provided an estimate of 172 Gg emission of BC from bio-fuel consumption for the year 1995. *Dickerson et al.* [2002] has estimated BC emission to be 510 Gg/yr for Indian sub-continent using fossil fuel and bio-fuel source for the base year 2000. The upper limit of there estimation was 820 Gg/yr for Indian region. *Reddy and Venkataraman* [2002] estimated the Indian BC emissions to be 380 Gg/yr for 1998–99. *Streets et al.* [2004] has estimated around 600 Gg/yr for BC emission for Indian region using EF prepared for developed countries for the base year 1996, which is even more

uncertain than estimate for China due to doubts about the emission factors of Indian vehicles, combustion technology, EF for dung-burning, degree of fuel adulteration. As evident from above description that the estimates over Indian region vary quite significantly. Hence, it is difficult to compare our estimated BC emission inventory with some earlier developed inventories directly. However, our BC estimates tend to be higher than the previous emission estimation [*Cooke et al.*, 1999; *Venkataraman et al.*, 2005; *Dickerson et al.*, 2002; *Bond et al.*, 2004], because in some cases, their estimation have omitted the bio-fuel sources and in some cases fossil fuel source. Moreover, a direct comparison is also difficult as developed inventories are for different years. The vast variations in the estimates are due to inherent uncertainties in the activity data as well as in emission factors. The emission factors of BC from different sources vary quite significantly due to use of a vast variety of technologies in each sector. In addition to this, most studies for estimation of BC emissions, the activity data (fuel consumption) have been taken from international sources like United States Environmental Protection Agency (EPA) and International Energy Agency (IEA) datasets while in our study, we have sourced our activity data from government official reports which are relatively more accurate. This is the first time that an effort has been made to generate gridded BC inventory from India's national level estimates covering major sources and micro level activity data using GIS technique.

[13] As we are using EFs for different fossil fuels developed by *Cooke et al.* [1999], hence the level of uncertainty in the present work, for fossil fuel is similar to uncertainty reported by *Cooke et al.* [1999], which of the order of a factor of two and the estimated value, as median value has been used for downscaling. Similarly, the emission factors for bio-fuel also depend on the kind of bio-fuel and the conditions under which they are combusted and the purpose for which they are burned. The emission factor for bio-fuel has been taken from *Venkataraman et al.* [2005] who have specified the uncertainty range as ±50%. Hence, in the present work, uncertainty for bio-fuel is also of the same order. It may, however, be noted that all the BC emission estimates generated so far carries a large uncertainty range (of the order of two or more) due to large uncertainties associated with the emission factors arising out due to measurements of BC and technological issues. Nevertheless, the present inventory estimations help in identification of the hot spot areas of BC emissions at district levels for India.

5. Conclusions

[14] The finely gridded emission inventory of BC has been prepared which indicated a significant growth of about 61% over the Indian geographical region during 1990s. The contribution of coal sector is dominated in the BC emission inventory. However, the vehicular emissions of BC have rapidly increased (112%) in this part of the world during 1990s followed by the coal. Although the per capita usage of fossil fuel and biomass is declining as they are being substituted by more efficient commercial energy source, the total consumption is still showing an increasing trend due to increase in population. This gridded emission inventory has provided detailed information about "Hot Spots", relative contribution of various sources and sector that can be targeted for mitigation. Present gridded inventory will not only improve the understanding on emission scenarios in the emerging economic country like India with their possible impacts but also can be used in the atmospheric chemistry transport models to study the distribution of its concentration and to estimate the radiative forcing.

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G. Beig and S. K. Sahu, Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pune 411008, India. (beig@tropmet.res.in)

C. Sharma, National Physical Laboratory, New Delhi 110011, India.