Black carbon emissions in India

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Abstract

Black carbon (BC) is a product of inefficient combustion and is involved with several detrimental environmental issues including enhanced global warming, ground level air pollution and melting ice in the Himalayas. Because BC has a relatively short atmospheric lifetime (days or weeks), reductions in BC emissions could achieve reductions in associated atmospheric effects far more rapidly than would be achieved with reductions in CO_2 emissions.

Global emissions of BC have been increasing over the recent centuries, reflecting the growth in industrial development. The majority of emissions arise from regions which are still going through significant growth – China and India being the current greatest regional sources.

Total emissions of BC are stabilising and may actually decrease in future. However, the extent of this decrease will be dependent on the rate of change of fuel use and the rate at which control strategies are adopted.

Since India is a significant source of global BC emissions, and is known to suffer direct effects of BC locally, this region would benefit greatly from immediate action to help mitigate emissions. This report summarises BC emissions in India now and for the next few decades and highlights areas where reduction strategies are most likely to be effective.

Acronyms and abbreviations

Accent v2	version 2 of the model created by the Atmospheric Composition Change – European Network
APCD	air pollution control devices
BC	black carbon
CAI	Clean Air Initiative (for Asia)
CLE	current legislation and economic development scenario
CPA	centrally planned Asia
DPF	diesel particle filters
EC	elemental carbon
EJ	Exajoule = 10^{18} J
FGD	flue gas desulphurisation
GAINS	Greenhouse Gas – Air Pollution Interactions and Synergies, IIASA
GDP	gross domestic product
GWP	global warming potential
IIASA	International Institute for Applied Systems Analysis
IGES	Institute for Global Environmental Strategies, Ministry of the Environment, Japan
IGP	Indo-Gangetic Plains, South Asia
INCCA	Indian Network for Climate Change Assessment
IPCC	Intergovernmental Panel on Climate Change
LPG	liquified petroleum gas
MAC	marginal abatement curves
MEFGI	Ministry of the Environment and Forests, Government of India
MFR	maximum (technically) feasible reduction scenario
Mt	million tonne
NAAQS	National Ambient Air Quality Standards
NCI	National Cookstove Initiative, India
OC	organic carbon
PFC	policy failure case
PSC	policy success case
PM	particulate matter
REAS	Regional Emission Inventory in Asia
REF	reference case
RF	radiative forcing
SAS	South Asia
SC	soot carbon
t	metric tonne
Tg	teragram = 1,000,000,000 tonnes
UN DESA	United Nations Department of Economic and Social Affairs
US EPA	United States Environmental Protection Agency
UNEP	United Nations Environment Programme
WHO	World Health Organisation

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1 Introduction

Black carbon (BC) is a sub-component of fine particles which results from the incomplete combustion of fuels such as coal and biomass. BC is short-lived in the atmosphere (a few days up to a few weeks) but still has a significant effect on climate in many regions of the world. Although it is widely accepted that BC is important in climate change, the extent of the effects of BC are still the subject of great debate due to BC having both potentially positive and negative effects on enhanced global warming. These include (Rono and others, 2011):

- negative effects due to radiative forcing – BC is a strong absorber of solar radiation and can therefore play a significant roll in global warming;
- indirect positive effects due to radiative forcing as a result of changes in albedo of snow and ice;
- positive or negative effects due to semi-direct effects on clouds and precipitation;
- negative effects on respiratory health;
- negative effects on crop production due to reduction of light on leaves;
- negative effects on soil, lowering growth and carbon sink capacity.

The overall effect of BC in any region will therefore be a result of local emission, global emissions, local climate and local geography. For example, in the Himalayas BC can amplify the effects of enhanced global warming while, in addition, causing surface dimming which can reduce crop productivity. BC has also been associated with disruption of the monsoon seasons in South and East Asia. The numerous atmospheric and climatic effects of BC mean that emissions of this species play an important role in the food and water security of these regions.

Over and above these regional and global effects, BC has a significant local effect as a constituent of the urban and indoor fine particulate pollution resulting from low-grade domestic fuel combustion for cooking and heating. The Indo-Gangetic Plains (IGP) stretch from Pakistan in the west to Nepal and Bangladesh in the east, with over 600 million inhabitants. The IGP are prone to dense layers of brown clouds consisting of BC, organic carbon (OC), sulphates and other aerosols. The BC in this region is known to arise from biomass combustion for cooking and heating but also from traffic, brick kilns and other industry. It has been estimated that two million deaths per year are caused by the use of indoor cook stoves, according to the World Health Organisation (WHO) – this is greater than the number of deaths due to malaria (US EPA, 2011).

BC has a relatively short atmospheric lifetime, from days to weeks, and therefore, unlike CO_2, offers the potential for effective and relatively quick mitigation measures for reducing negative climatic effects. In addition, action to reduce BC emissions could avoid over 1.6 million premature deaths from inhalation of smoke from indoor cooking as well as potentially reducing warming on a short time-scale (Rehman and others, 2011).

This short report provides a summary of emissions of BC from India based on an extensive literature review. Information is given on emissions from different sectors in each country with an aim to determining the sources of most concern and, at the same time, the sources most likely to achieve reductions through emission control strategies. Predictions for emissions to 2020 and beyond are included to give an indication of the sectors of most concern moving forward. Finally, a discussion is provided on potential pathways to reduce BC emissions from India.

2 Emission inventories

All the authors who have produced or reviewed BC inventories, such as Bond and others (2004), Sahu and others (2008) and Kopacz and others (2011) stress that past, present and future emissions of aerosols in general, and BC in particular, are difficult to quantify with any certainty. Kopacz and others (2011) go as far as to say that past, present and future emissions of BC are 'highly uncertain'.

Particulate emissions from sources such as small industrial processes and domestic fuel use are extremely difficult to quantify. Further, the particulates released from these sources are a combination of primary particles and secondary reaction products which form downwind of the source. Cloud chemistry, carbon type and particle type add to the confusion. In addition, the most common methods used to measure BC are based on thermal or themo-optical systems, both of which are based on indirect measurement methods and are therefore prone to error and disagreement in results.

Emission inventories for species such as BC are commonly prepared in one of two ways:

- **bottom-up studies**, based on fuel consumption and generalised emission factors;
- **top-down studies**, which rely on measured ratios of components (commonly OC, organic carbon, versus BC) of particles measured in different regions and use these to extrapolate backwards to probable sources.

For bottom-up studies, BC emission estimates are often based on PM (particulate matter) and $PM_{2.5}$ (fine particulate matter below 2.5 µm in diameter) emission factors. PM and $PM_{2.5}$ estimates can be augmented by use of a computer programme such as the US EPA's SPECIATE 4.2 database to estimate the approximate contribution from BC, based on estimated mass fractions for different source categories (Arctic Council, 2011). This does not necessarily mean that the data on these PM and $PM_{2.5}$ emissions are any more accurate than those for BC. However, more data are available for PM and $PM_{2.5}$ as these species have been measured for longer periods historically and monitoring is currently required under many national emission standards or national ambient air quality standards (NAAQS). Monitoring of fine particulates is particularly challenging since these particulates are a combination of both primary and secondary particles. The error in fine particulate emission estimation is further increased by the use of generic activity data based on process models or surrogate information. The IEA CCC has produced several reports on this subject previously (Sloss, 1998a,b; 2004) and the interested reader is referred to these documents for further information.

Emission factors for BC from different sources have been collated and are shown in Table 1. Although the emission factors vary noticeably between sources, they generally remain within the same order of magnitude for most sources. The exception would appear to be coal combustion where emission factors can vary significantly from study to study. In some cases these emission factors vary depending on where they are applied geographically – for example, emission factors for coal combustion in undeveloped countries were estimated by Cooke and others (1999) to be almost five times higher than those for developed countries.

Section 2.1 summarises global emissions of BC in order to put emissions from India into perspective. This section also discusses the issues and problems associated with estimating emissions from developing regions. Section 2.2 then concentrates on inventories produced specifically for India.

2.1 Global emission inventories

It is not possible to produce a summary of BC emission inventories without mentioning the GAINS model (Greenhouse Gas – Air Pollution Interactions and Synergies) produced by the International Institute for Applied Systems Analysis (IIASA) in Austria. The GAINS model is based on country-

Table 1 Comparison of BC emission factors from the literature, g/kg (Bond and others, 2004; Mitra and Sharma, 2002; Sahu and others, 2008)

Coal	Diesel	Bio-fuel	Petrol	Kerosene
Cachier and others (1989):				
3	5	2.5 (wood)	0.1	0.3
		2 (dung)		
Cooke and others (1999):				
2.13 (U#)	10 (U)	0.15	0.03	
1.22 (SD#)	10 (SD)			
0.75 (D#)	2 (D)			
Gadi and others (2001):				
		0.16–2.5 (wood)		
		2.7–9.03 (dung)		
		0.2–2.7 (agri-residue)		
Dickerson and others (2002):				
0.0001 (power plant)	12	1 (residential biofuel)	0.23	–
0.32 (industrial)				
Reddy and Venkataraman (2002b):				
1	0.7	0.28 (firewood)	–	0.3
		0.328 (dung)		
		0.446 (agri-residue)		
Streets and others (2004):				
0.056–0.6 (industry)	–	1	–	–
0.12–3.7 (domestic)				
Bond and others (2004):				
0.002–0.009 (power)	0.06–4 (residental)	0.85 (firewood)	–	0.9
0.013–1.2 (industry)	3.4–4.4 (industry)	0.53 (dung)		
0.76–5.4 (residential)		1 (agri-residue)		
Venkataraman and others (2005):				
–	–	0.50 (firewood)	–	–
		0.85 (dung)		
		0.145 (agri-residue)		

U undeveloped countries
SD semi-developed countries
D developed countries

and regional-specific emission factors, known control technology applications and nation-level activity data. The GAINS model is a detailed bottom-up inventory tool which covers factors such as abatement technology and fuel type to give more accurate emission estimates than most bottom-up estimates. Emission factors for BC, OC and PM are included. The emission rates for BC and OC are 'decoupled' from the fossil fuel quality parameters and are therefore independent from the $PM_{10/2.5}$ estimates. However, comparison of these different estimates allows confirmation and verification. Many of the inventories discussed below used GAINS model information in their studies. More details on the GAINS model can be found at: http://gains.iiasa.ac.at/index.php/gains-asia

One of the most cited global inventories for BC is that of Bond and others (2004), which is a bottom-up estimate. The Bond inventory was calculated using mass-based BC emission factors and country-level fuel use and activity data. The study takes into account regional technologies and emission controls. Activity data for the inventory was for 1996 and the results are therefore somewhat dated. However, the work by Bond and others formed the basis of most of the inventories published since 2004.

The work by Bond and others (2004) was not the first to estimate BC emissions, but rather was the first to consider different emission factors for different types of combustion processes. Since the amount of BC formed varies with the combustion system and combustion characteristics, emission factors vary from source to source and fuel to fuel. Bond and others therefore reviewed the literature to obtain the most representative emission factors, placing emphasis on those which were actually obtained from direct measurements. The authors also collated data on the different types of combustion systems and controls used in each region globally. The interested reader is recommended to read the original paper as this gives an extremely valuable and detailed discussion of the calculations and assumptions involved in the inventory and the estimation of uncertainty.

In the Bond and others (2004) study, the global total BC emissions were estimated at 8 Tg/y of which 38% is from fossil fuels, 20% from biofuels and 42% from open burning. The uncertainty of the emission inventory was said to be at least a factor of two, meaning that the total global emissions of BC could be anywhere between 4.3 and 22 Tg/y.

The same authors provided an update of this work in 2007 (Bond and others, 2007), estimating the history of emissions between 1850 and 2000. Emissions were calculated to have grown from 1000 Gg in 1850 to 2200 Gg in 1900 and had reached 4100 Gg by 2000. Although coal was estimated to be the greatest contributor to BC between 1880 and 1975, it was overtaken by emissions from biofuels in 1975 and by diesel engines around 1990.

Anenberg and others (2011) produced an inventory suggesting that around 93% of global BC emissions come from three major sectors: residential (38%), industrial (including non-road transportation; 29%) and transportation (on-road only; 26%). However this varies by region and in India, 62% of the BC emissions are from the residential sector. On a global scale, East Asia (largely China) contributes 32% of global anthropogenic BC emissions, more than double the contribution from any other region. India contributes around 12%.

Koch and others (2007) produced a global BC inventory (Table 2) based on a combination of models and inventories published between 1995 and 2005, including that of Bond (2004). The inventory is divided into major global regions, as shown, and concentrates on what they term 'non-biomass burning anthropogenic emissions' – which includes industrial emissions from all sources but excludes biomass burning. India comprises most of South Asia. The table also includes an estimate of the amount of the BC emissions that are exported from the region. Table 3 then shows the breakdown of the emissions into sectors, with biomass and residential burning clearly being the greatest sources of BC emissions globally. The aerosol forcing of the emissions from each sector, in terms of Watts per square metre, are also included in the table. From this it is clear that tackling emissions from biomass and residential combustion should be a priority with respect to reducing warming effects.

In their conclusions, Koch and others (2007) note that the BC emissions estimated by their model are 'significantly' under the values reported from actual measurements for some areas, especially Southeast Asia. This is apparently common with many modelling studies and is due to the lack of data

Table 2 Annual global BC emissions from non-biomass burning (industry) – regional contributions (Koch and others, 2007)

Region	Emissions from non-biomass burning		Amount exported
	Tg/y	%	%
Southeast Asia	1.5	18.3	67
North America	0.4	4.9	NA
Europe	0.5	6.1	67
South Asia	0.6	7.3	80
Other	1.5	18.3	–
Total	8.2	100	

Table 3 Global BC emissions: sectoral contributions (Koch and others, 2007)

Sector	Emissions of BC		Aerosol forcing	
	Tg/y	%	x 100 W/m^2	%
Industry	1.1	13	4.6	13
Residential	2.1	26	9.4	28
Power	0.03	0.4	0.4	1
Transport	1.3	16	5.6	16
Biomass	3.7	45	14.3	42
Total	8.2	100		

on total emissions in these areas, especially from hard to quantify sources such as domestic fuel use.

Cofala and others (2007) compared global emission estimates for BC published for the years between 1980 and 2000 and found that they varied from as low as 4954 Gg/y to 12,610 Gg/y (excluding uncertainty ranges). The disagreement between estimates was put down to different representations of emission sources (emission factors) and their activities. For comparison, a report commissioned by the Arctic Council (2011) on emissions of BC to the Arctic concentrated on estimating inventories for Scandinavia, Canada and the USA. Even for these developed regions, the use of different methodologies and source categories leads to incomplete data and significant uncertainties.

It is generally agreed that the majority of the disagreement between emission inventories is due to differences in the emission factors used. Clearly more country- and source-specific emission factors would help improve emission inventories. However, Lu and others (2011) note that, even when emission factors have been measured in field tests in different countries, there is a surprisingly high uncertainty, reflecting the variation in combustion conditions and characteristics in many of the small-scale combustion systems. This means that emission factors will always be a ‘best guess’ for sources such as domestic and industrial combustion.

Koch and others (2009) compared various model estimates of BC emissions and concentrations in different regions against actual measured data (aircraft monitoring) and found, unsurprisingly, some disagreement. There was bias towards underestimation of BC in some regions especially in biomass burning regions where the ratio of the model results to the measured data was 0.4 to 0.7. Further study was recommended to close the gap between models and observations.

In addition to these bottom-up studies, top-down studies can help fill gaps in the data and provide confirmation of emission estimates. The majority of information on BC emissions in remote locations comes from either lab or remote field observations which are carried out far from the original source (Rehman and others, 2011). This means that source apportionment is performed by modelling and estimation via the top-down approach. According to Gustafsson and others (2009), several top-down studies concluded that between 50% and 90% of the BC in South Asia arises from fossil fuel combustion. Conversely, bottom-up studies were reported to estimate that only 10-30% of the BC originates from fossil fuel combustion. The large discrepancy between the results from the different methods is not really surprising as both methods are unavoidably but fundamentally flawed. In the top-down studies, the ratios used to extrapolate to source were based on data from other regions which may not be representative of South Asian combustion processes and the formation of secondary aerosols cannot be accounted for easily. In the bottom-up approach there is a strong dependency on assumptions made on fuel type and efficiency of combustion which, again, may not be representative of the South Asian situation.

Kopacz and others (2011) warn that the under and over estimates of BC are common with no consistent bias, and emphasise that more work is needed to reduce the uncertainties in emission inventories for BC. Disaggregation of the contributions of the different sectors (such as transport, domestic combustion and so on) would help to guide the optimisation of mitigation strategies. Modelling would then help to determine the most appropriate regions to target to allow emissions reductions to achieve the greatest contribution to BC reduction in the areas of most concern.

2.2 Inventory for India

Baseline estimates for BC for India from 1990 to 2030, as estimated by the GAINS model, are shown in Table 4. Residential combustion dominates the inventories for all years with combustion from energy and transformation industries being low and decreasing over time. BC emissions from combustion in the manufacturing industry are predicted to grow significantly in future, as are ‘emissions from other mobile sources and machinery’ (not road transport) (*see also* Chapter 3).

In the much-cited paper by Bond and others (2004), emissions of BC from India were estimated at 483 Gg/y in a range of 307–1035 Gg/y, based on emissions from fossil fuel and biomass combustion, and excluding open burning. This put the total BC emissions from India at around 10% of the global total (4626 Gg/y), implying that India was the second most important region with respect to BC emissions after China with 1365 Gg/y (almost 30% of emissions).

Bond and others (2007) estimated that BC emissions from coal use in India increased from 28 Gg in 1950 to 55 Gg in 2000, an increase of 95%. However, this increase was due to an actual increase of 1100% in coal use during this period, indicating that the efficiency of coal use had increased and the emission factor lowered considerably over time. This potential for decrease in emissions due to an efficiency improvement was termed as ‘sectoral shift’ – a move from inefficient to more efficient combustion systems by either upgrading, retrofitting or changes in technology. For India the sectoral shift between 1950 and 2000 was –76%, comparing well with the –82% reported for the EU and –96% for North America and considerably greater than the –23% reported for China. This also suggests that, since 2000 and beyond, there is potential for more of a sectoral shift in emissions from coal use and that further reductions in emissions and improvements in efficiency are possible.

Table 5 compares estimates from published emission inventories (bottom-up), including details on the values used in the calculations, and on ambient measurements, as collated by Gustafsson and others (2007). In the emission inventories, the total for the estimates are in relative agreement, with the total emission in the region of 0.1–0.5 Tg/y. This is perhaps not surprising considering such gross national estimates are probably based on similar emission factors and activity data. The estimates for the relative contributions from fossil fuel versus biomass combustion are also in relative agreement.

Table 4 GAINS baseline emissions of BC for India, Gg C/y (http://gains.iiasa.ac.at, 2012)

Sector	1990	1995	2000	2005	2010	2015	2020	2025	2030
Combustion-energy and transformation industries	2	3	2	2	1	1	1	1	1
Non-industrial combustion (residential)	471	498	511	590	628	623	616	610	604
Combustion in manufacturing industry	82	109	145	231	255	297	331	354	381
Production processes	7	7	5	5	5	5	5	5	6
Road transport	33	44	62	78	78	31	31	34	37
Other mobile sources and machinery	16	23	32	44	58	71	86	102	120
Waste treatment and disposal	18	13	14	15	16	16	16	17	18
Agriculture	69	70	69	64	65	63	62	60	59
Total	698	766	842	1029	1104	1107	1149	1184	1227

Table 5 Apportionment of Indian carbonaceous aerosols between fossil fuel and biomass combustion (Gustafsson and others, 2009)

Study	BC from fossil fuel combustion	BC from biomass combustion	Methods/comments
Emission inventories			
India inventory (Reddy and others 2002a,b)	29%	71%	0.1 Tg/y (100 Mt/y) fossil fuel and 0.25 Tg/y biomass
South Asia inventory (Dickerson and others, 2002)	12–45%	55–88%	0.059–0.37 Tg/y fossil fuel and 0.45 Tg/y biomass for India
(Bond and others, 2004) Global inventory	~30%	~70%	0.18 Tg/y fossil fuel, 0.33 Tg/y biofuel, 0.087 Tg/y open burning for India
South Asia biofuel study (Venkataraman and others, 2005)	25%	75%	India-specific emission factors and fuel usage
Ambient measurements			
INDOEX flights over Indian Ocean (Novakov and others, 2000)	80%	20%	EC:TC ratio for three flights
INDOEX flights over Indian Ocean (Mayol-Bracero and others, 2002)	60–90%	10–40%	EC:TC ratio for 13 flights
Atmospheric BC in Maldives (Stone and others, 2007)	40–50%	30–40%	Positive matrix factorisation with EC and multiple elements
Maldives + India (Gustafsson and others, 2009)	32 ±5%	68±6%	Radiocarbon analysis of ambient filter-based SC, range of 66–76% for biomass
Maldives + India (Gustafsson and others, 2009)	54±8%	46±8%	Radiocarbon analysis of ambient filter-based SC, range of 45–52% for biomass

INDOEX = Indian Ocean Experiment

However, the data from the ambient monitoring studies suggest that the relative contributions from fossil fuel and biomass combustion may be more equal.

Gustafsson and others (2009) used radiocarbon (^{14}C) techniques to determine the contribution of different sources to BC emissions in South Asia. Two sites were chosen, one in the Maldives and one in Sinhagad, West India. The results, included in Table 5, indicated that more (68±6%) soot carbon (SC), measured by chemothermal-oxidation and representing a more 'recalcitrant' [sic] portion of the BC spectrum, comes from biomass combustion than fossil fuel combustion. However, slightly more (54±8%) of the elemental carbon (EC) arises from fossil fuel combustion.

Sahu and others (2008) produced a bottom-up inventory for BC in India based on national and regional statistics including the 84 thermal power plants, 12 steel plants and 87 cement plants operational in 2001. Data were also estimated for 1991 when the same number of steel and cement plants but only 71 thermal power plants were in operation. However, although the number of power plants did not grow significantly between 1991 and 2001, many of the existing plants increased in capacity. These large-scale point sources consumed more than 95% of the coal used and less than 5% was used in sources such as bakeries, the brick industry and other industrial processes. Sahu and others used the emission factors cited by Cooke and others (1999; shown in Table 1). Total BC emissions from India were estimated at 1343.78 Gg in 2001, a 61% increase from 835.50 Gg in 1991. This was in general agreement with the other emission estimates included in Table 1.

Reddy and Venkataraman (2002a) have carried out perhaps the most significant study into BC emissions from different power-using sectors in India. Total BC emissions from fossil fuel combustion for 1996-97 were calculated to be 0.10 Tg/y with diesel oil contributing to 50% of this total and coal to 40%. The major sources of BC were as follows:

- transportation 58%
- brick kilns 24%
- utilities 15%
- 'other' 3%

More details from this study on emissions from individual sectors are discussed in the following sections. Emissions of BC from fossil fuel combustion in India amounted to only 29% of the total BC emissions, the remainder coming from biomass burning. Interestingly, a previous study by the same authors from 2000 estimated BC emissions from fossil fuel combustion in India at 0.25 Tg/y, more than twice the more recent estimate. This was due to the use of emission factors which overestimated BC emissions from the different fuels.

Lu and others (2011) estimated BC emissions in India from 1996 to 2010, noting an increase in energy consumption in every sector during this period. It is therefore not surprising that emissions of BC were found to increase from almost all sectors. The growth in BC emissions in India, unaffected by factors such as control technologies, was governed largely by the trend in energy consumption. The resulting emissions of BC are summarised in Table 6. There have been increases in BC emissions from all sectors. Emissions from power plants were not as significant as emissions from industry; however, the relative overall increase in emissions from power plants and coal combustion (66%) was much greater than from any other source or individual fuel type. Lu and others (2011) compared their emission estimates with those of the other publications (Bond, Streets, Venkataraman and so on) and found that there was significant disagreement, largely due to the different emissions factors applied in the different studies.

One of the largest problems in estimating BC emissions from areas such as India is the seasonal variation – observed BC concentrations in snow in some regions can be lowered by a factor of two during the monsoon season. Unless emission estimates are adjusted to take this seasonal variation into account, it is important to determine whether the emission estimates fairly reflect the yearly average emissions. The majority of this seasonal variation is due to changes biomass burning activities.

Table 6 Emissions of BC in India, 1996-2010, Gg/y (Lu and others, 2011)

Source	1996	2000	2004	2008	2010
Power plants	3	4	4	5	5
Industry	155	168	198	217	227
Residential	402	421	481	563	579
Transport	80	88	88	107	111
Coal	177	172	209	276	295
Oil	117	126	124	153	159
Biofuel	338	373	426	449	454
Other	8	10	12	14	15
Forest and savanna burning	19	17	19	16	19
Agriculture and waste burning	60	56	59	71	74
Total	718	753	850	979	1015

Further, the atmosphere can transport emissions relatively long distances making local inventories somewhat less than complete. A glacier in the Tibetan Plateau and Tienshan Mountains has been shown to contain the largest amounts of BC in the Asian glaciers and it is believed that emissions from Europe contribute significantly to this total (Kopacz and others, 2011). The work by Kopacz and others on BC deposition in glaciers in Asia demonstrates the huge variations and uncertainties in data on BC emissions and deposition. During the monsoon season, India and China contribute around 75% of the BC deposited in the Everest region whereas in the pre- and post-monsoon seasons the majority of the BC comes from more local locations in China, Nepal and the India Ganges Valley.

Although there may be disagreement between these inventories, there is general agreement on the major sources and regions that are of concern. The following sections look at BC emissions from individual sectors in India.

2.2.1 Power production

Power generation is responsible for less than 1% of global BC emissions (Anenberg and others, 2011). Although the proportion may be higher in India, power production is far from being the most important source of BC emissions in the country. However, it is important to make sure that these emissions are not likely to become an issue in future with the rapid growth that is forecast in the power sector in India over the coming decades.

According to Sahu and others (2008) emissions from coal combustion in India increased from 451 Gg in 1991 to 709 Gg in 2001, due to a 57% increase in the use of coal. However, during this time the power production from coal increased by 87% due to an increase in efficiency at some plants. Mitra and Sharma (2002), using the same emission factors and activity data as Sahu and others (2008), estimated emissions of BC from coal combustion at 157 Gg/y in 1995 and calculated that this had increased to 697 Gg/y by 2009. As mentioned in Section 2.1 *above*, although coal use has increased significantly in India over the past decades, emissions of BC have not increased at such a great rate due to a sectoral shift and an increase in plant and process efficiencies.

Perhaps the most focused study, with respect to BC emissions from fossil fuel combustion, is that by Reddy and Venkataraman (2002a). Although somewhat dated, it would seem that the report has not been updated by the authors or anyone else since. The study produced a spatially resolved map of emissions over the Indian region based on data for 1996-97. Reddy and Venkataraman used as much study-specific information as was available. They noted that there were no estimates of fossil fuel consumption or pollutant emissions compiled by Indian regulatory authorities that could be cited. The authors used India-specific emission factors, taking into account that Indian coals tend to have significantly higher ash and lower sulphur content that the global average. Around 73% of the coal use in India is used in utilities and the ash content varies from 18% to 50% with a consumption-weighted average of 39%. The study also took into account any air pollution control devices (APCD) in place which may reduce particulate and BC emissions. As much as was possible, emissions were estimated on a plant-by-plant basis. With respect to emissions from power generation, coal contributed around 88% of the $317x10^3$ GWh of installed capacity in 1996-97. In the industrial sector, all major industrial units in India have their own power generating facilities.

For emissions from utilities, the emission factor for PM were calculated based on the current emission limit (150 mg/m^3) and boiler sizes, the AP-42 emission factors (published by the US EPA) and assuming two levels of particulate control in the APCD – 50% and 100%. Based on the AP-42 emission factors, it was suggested that the Indian emission limit of 150 mg/m^3 was probably not being met under most operating conditions. But the authors agreed that this would need to be verified with actual monitoring. The emission factors for BC were estimated based on the particulate matter emission factors based on proportional analyses data cited from previous studies.

The results of Reddy and Venkataraman (2002a) suggested that, if the existing APCD in India are applied effectively to all plants and are running full-time, then total $PM_{2.5}$ emissions for 1996-97 would be 0.49 Tg/y of which 17% would be black carbon. However, assuming a more realistic 50% control scenario for APCD, the total $PM_{2.5}$ emissions would amount to 2.0 Tg/y of which 5% would be BC. The emission factors used, based on APCD working 50% of the time, are shown in Table 7.

Lignite combustion in the power sector was reported to result in negligible amounts of BC emissions. For comparison, emission factors for BC from natural gas use were zero and for petroleum fuels were 0.17 g/kg or below (diesel internal combustion engines).

Despite power plants and industrial units accounting for 76% of primary energy consumption, the BC emissions from these sources was only 18% of the total emissions from this sector (15% from utilities

Table 7 Emission factors for coal and lignite combustion in Indian sources, 50% control scenario (Reddy and Venkataraman, 2002a)

Source	Emission factors, g/kg	
	$PM_{2.5}$	BC
Coal		
Utilities (power generation)*	8.10 (1.10–19.00)	0.77 (0.01–0.18)
Industrial boilers*	1.36 (1.19–1.42)	0.0095 (0.0083–0.0099)
Domestic, brick kilns, rail†	12.20	1.83
Lignite		
Utilities	2.04 (1.86–3.91)	–
Domestic, brick kilns	4.60	0.18

* consumption weighted average of plant-wise values
† uncontrolled

alone). This is due to the higher efficiency of combustion in these systems in comparison with the low efficiency systems used in the residential sector.

2.2.2 Industry

In general, industrial practices have improved in efficiency in recent decades. For example, producing 1 t of pig iron in the year 1830 took 3.5 t of coke. By the middle of the 20th century, this had dropped to only 0.53 t of coke (Bond and others, 2007). Therefore, although we can assume that emissions of BC from industry in India will have increased with increasing fuel use, changes and improvements in the technology mean that the emission factor must be adjusted from period to period and that emissions do not grow at the same rate as fuel use.

All major industrial units in India have power-generating units on site to meet some or all of the power requirements and the majority of these run on coal. Coal was used at the seven integrated steel plants in operation in India in 1996-97 with a total production of 18.8 Mt. The power for these plants was mainly coal with only small quantities of oil and gas. Coal was also the major fuel in the cement plants, pulp and paper industry, non-ferrous metal industry and brick-making industry. Petroleum is the major fuel used in heavy machinery used in industries such as coal mining.

According to Reddy and Venkataraman (2002a), industrial boilers in India fire high calorific content and low ash coals. Most of the boilers are cyclone furnace, spreader stoker, underfed/overfed stokers fitted with APCD such as multiple cyclones, ESP (electrostatic precipitators) and baghouses. As with the coal study, discussed in Section 2.2.1 above, Reddy and Venkataraman estimated emissions from this sector assuming a 50% rate of APCD use across all plants. The lower ash content of the coal use means that the BC emission factor was also lower at 0.0095 (0.0083–0.0099) g/kg. With respect to total emissions in India, BC from fossil fuel combustion in the iron and steel industry was estimated to be only 1% of the total. Brick-kilns contributed 23%, and emissions from fertiliser and cement production were negligible.

Khare and Baruah (2010) estimated emissions of various pollutants from coke ovens in India firing high sulphur coals. Northeast Indian coals differ from other Indian coals in that they are high in sulphur and volatile matter while being low in ash and moisture. These coals cannot be used in energy or industrial applications but are used in the coke oven industry, although they may be used in coal-fired plants in the future. Although currently only used in the cement industry and blast furnaces, these Northeast Indian coals may also be used for making coal for steel production in the future. Emission factors for BC were estimated at between 0.007 and 0.03 kg/t resulting in total emissions of 0.71–2.9 t/y from the current coke making industry in India.

Around 4% of lump coal is fired along with low-grade biofuels in brick kilns. These kilns are of low efficiency, with temperatures similar to domestic fuel combustion and similar emission factors. Small-scale coal combustion, including brick kilns, rail locomotives, and domestic coal use contributed to 23% of BC emissions from fossil fuel combustion in 1996-97.

Looking back at Table 4, it can be seen that combustion in manufacturing industries in India are a significant source of BC emissions (255 Gg/y in 2010, comprising 23% of the total emissions), and brick kilns are the sector of most concern. The data reviewed in this section highlight that BC emissions from industry are often the result of the use of low-grade fuels and from dated and inefficient systems and processes.

2.2.3 Transport

The major source of BC emissions from fossil fuel combustion in India is the transport sector which contributes 58% of emissions, although road transport accounts for only 16% of the energy consumption in the country. Reddy and Venkataraman (2002a) estimate that shipping and aviation contributed less than 1.5% of fuel use in India in their 1996-97 study period. The majority of the transport emissions are from the heavy-duty trucks (around 52% of BC emissions from the transport sector). Around 0.05% of coal is used together with other fuels in rail locomotives. The emission factors used are the same as those for domestic fuel combustion because of the similar temperatures of combustion.

Particulate matter emission factors for road transport have been estimated for Indian vehicles at between 0.36 g/kg for unleaded petrol vehicles without a catalytic convertor, and up to 4.42 g/kg for heavy duty diesel vehicles. Of this PM, BC is estimated to contribute anywhere between 20% and 80%, according to different studies (Reddy and Venkataraman, 2002a).

Mitra and Sharma (2002) estimated that diesel consumption in India would increase by an order of magnitude from 6.6 Mt/y in 1975 to 65.5 Mt/y in 2009. From this, and based on an emission factor of 10 g/kg, the emissions of BC were estimated to increase from 66 Gg in 1975 to 655 Gg in 2009. During the same period, gasoline use was only expected to increase from 1.3 Mt/y to 8.1 Mt/y resulting in a less significant increase in BC emissions from 2.7 Gg/y in 1975 to 17.2 Gg/y in 2009 (based on an emission factor of 0.15 g/kg). Kerosene use was expected to increase from 3.1 Mt to 12.2 Mt resulting in BC emission increase of 6.6 Gg to 26 Gg between 1975 and 2009.

As was the case for emissions from residential combustion, emissions from the transport sector in India are hard to quantify due to a lack of data on emissions from individual vehicles and limited data on the number and types of vehicles on the road. However, since vehicles tend to have a much shorter lifetime than power plants or industrial processes, the replacement period for vehicles is relatively short and therefore the uptake of control technologies and improved combustion systems and fuels is much faster.

2.2.4 Residential

The low combustion temperatures in domestic coal use lead to less efficient combustion and greater emissions of particulates. Further, particulate emissions from these sources are uncontrolled. The measured BC fraction of particulate matter for domestic coal combustion in India is 15% and 4% for lignite combustion. The domestic sector accounts for only 0.12% of the coal consumption in India and results in around 1% of the BC emissions. It is estimated that, nationally, coal and charcoal are only used as cooking fuel in about 1.9% and 0.40% (respectively) of households in India. Most stoves cofire biomass with coal and this is estimated to cause around 24 kt BC/y out of a total of 154 kt BC/y for all cookstoves. The major fuels used are wood (48.7%), LPG (24.7%) and dung (10.6%) (Venkataraman and others, 2010).

Biomass fuels are estimated to account for 25% of the global emissions of BC and around 50% of emissions from human activities (Rehman and others, 2011). According to Venkataraman and others (2010) around 80% of the 160 million rural and 58 million urban households use solid biofuels for cooking and heating.

Reddy and Venkataraman (2002b) estimated BC emissions from combustion in India for 1996-97 and found that biomass contributed 245 Gg/y of which 50% (123 Gg/y) came from fuel wood and 22% (54 Gg/y) came from crop wastes. Dung-cake and forest fires contributed more to OC emissions than to BC emissions. Spatial maps of India were produced showing areas of most concern with respect to pollutant emissions to be on the east side of the country.

Sahu and others (2008) reviewed previously published emission inventories for BC emissions from biofuels in India and found estimates ranged from around 380 Gg (for 1998-99) up to 820 Gg (for

2000) showing that the estimates are varied but still within the same general order of magnitude. The estimates vary, as always, due to the different emission factors and activity data used in different studies.

The WHO recommended level for 24-hour PM exposure is 25 $\mu g/m^3$. BC concentrations from inefficient mud stoves can exceed this by a factor of five (Rehman and others, 2011). The near-surface concentrations of BC over the North Indian Ocean (regional background concentrations) are commonly around 0.5–1 $\mu g/m^3$, significantly lower than the 10->100 $\mu g/m^3$ measured in the IGP region (Rehman and others, 2011).

Rehman and others (2011) have carried out source monitoring studies on BC emissions, indoor and outdoor, during cooking hours. Peak concentrations for indoor BC during cooking episodes reached as high as 1000 $\mu g/m^3$. Although this type of data is of limited use for emission inventories, Rehman and others (2011) emphasised that the significant variation in concentrations and emissions between cooking hours and non-cooking hours (up to a factor of 10-30 difference) could mean that satellite-based aerosol studies, based on once-daily measurements, could significantly underestimate the potential BC loading of the atmosphere. The imprints of the cooking hour emission peaks were seen both in the local village as well as on the highway. Cooking and heating patterns may vary seasonally which may explain some of the seasonal variation in emissions mentioned earlier.

It is clear that biomass combustion is the major source of BC emissions in India, as is agreed by all of the published data. However, these estimates tend to be based on a limited pool of emission factors and activity data. Although emissions from sources such as power plants and industry can be evaluated relatively accurately, since individual source data and official fuel supply statistics can be found, this is not true for residential combustion. Much of the fuel used – wood and agricultural waste – is sourced locally and no records are kept of how much is used. There is also no record of how many cookstoves are in operation in India or on the type and efficiency of each. It is therefore likely that the actual emissions of BC from this sector could deviate quite significantly from the numbers quoted in the literature. However, it is also clear that this is one of the most obvious targets for BC emission control in future and it is therefore far more important to concentrate on means to reduce emissions from this sector rather than on further measurement.

2.3 Comments

Estimating emissions of BC is not simple, due to the variability of emission factors between sources and fuels and between different regions of the world. The majority of published emissions are based on a limited pool of emission factors and activity data and are therefore in general agreement. However, these data could be further improved by continued developments in BC measurement and monitoring and work towards improving the agreement between emissions and atmospheric loads as estimated by emission inventories and those measured in practice in atmospheric studies. Spatially defined maps will help determine major regions most suitable for targeting reduction programmes.

Despite the uncertainties in the global and regional emission inventories, it is clear which areas, sources and sectors are the most significant and which would therefore be most appropriate to target for reduction. In India, the significant increase in coal combustion for power generation has resulted in an increase in BC emissions in this sector but, because of the inherent efficiency of these large-scale combustion systems, power plants are not the most suitable candidates for BC control. That is not to say that Indian power plants would not benefit significantly from pollution control technologies to reduce emissions of particulates, SOx, NOx and CO_2, but that the potential for achieving a significant national reduction in BC emissions specifically is limited. However, although coal combustion is not a major source of BC emissions in India, emissions monitoring from this sector would serve to confirm emission factors and to ensure that air pollution control devices are performing as they should be.

Many of the existing industries in India, especially the brick kilns, are relatively old and, in western terms, out-dated. These systems use low grade fuels and are inefficient and therefore cause significant BC emissions. However, the means to reduce these emissions is relatively clear – changes in fuel use, changes in industrial processes to improve efficiency and even the complete overhaul of some industries to more modern technologies could all achieve both significant reductions in BC emissions whilst, at the same time, improving process economics. This may involve a significant initial investment in some sectors but should be cost-effective over time.

3 Projections to 2020 and beyond

Globally, BC has been increasing in the atmosphere since the late 1800s. The first growth period was as a result of activities in North America and Europe. The second growth period, after 1970, was largely due to emissions from East Asia. Data from snow analysis in the Arctic suggest that the maximum atmospheric BC burden was reached in the 1960s with a slight reduction thereafter (Skeie and others, 2011).

Predictions of potential future changes in emissions of BC have been estimated by a few authors, based on different scenarios for future growth, development and legislative action. These studies are summarised in the following sections.

3.1 Growth and development in India

Growth in the Indian population and economy is almost unprecedented. India is expected to be among the leading markets for basic materials by 2015 due to rapid demand growth, becoming the fourth largest market for coal by 2015 with demand approaching 790 Mt/y (Ray and others, 2009). However, since efficient coal combustion for power generation is not a significant source of BC in India or elsewhere, this should not result in any increase in BC emissions. In fact, the expanded electrification of the country and the ongoing provision of electricity and power to more and more remote regions should actually result in a decrease in the use of biomass and other less efficient fuels for domestic cooking and heating.

India has limited legislation on emissions. There are no requirements for reductions in SO_2 or NOx emissions, although new plants must be built with space for the potential future installation of flue gas desulphurisation systems (FGD). Particulate controls are present on all plants but questions have been raised as to whether these are run efficiently (Reddy and Venkataraman, 2002a).

India currently has air quality standards for fine particulates. The annual and 24-hour average limits for PM_{10} are 60 and 100 µg/m^3 respectively and for $PM_{2.5}$ are 40 and 60 µg/m^3 respectively. The US EPA NAAQS for $PM_{2.5}$ are somewhat lower at 15 µg/m^3 as an annual mean and 35 µg/m^3 as a 24-hour mean. The US EPA NAAQS 24 hour mean for PM_{10} is actually higher than that for India at 150 µg/m^3 (CAI-Asia, 2010). Whether these standards in India are actually met, is unclear.

3.2 Estimates for future BC emissions

One of the earliest projections for future emissions was that of Streets and others (2004), who used the IPPC (Intergovernmental Panel on Climate Change) scenarios to project global BC emissions out to 2020 and 2030. The baseline emission estimates for this work were the data from Bond and others (2004). The scenarios can be summarised in Table 8. Under all scenarios, BC is expected to decline globally, although there may be increases in some sectors in some regions of the world. Global emissions of BC were predicted to decline from 8 Tg in 1996 to 5.3–7.3 Tg by 2030 and to 4.3–6.1 Tg by 2050.

Streets and others (2004) did not create emission estimates for individual countries, and so for the results for India, we must look at the estimates for South Asia. South Asia is commonly defined as the region including Afghanistan, Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan and Sri Lanka. Emissions of BC for South Asia were expected to increase from 715 Gg/y (in 1996) to a maximum of 875 Gg/y in 2030 under scenario A2. Scenario A1B also resulted in an increase of BC to 829 Gg/y in 2030. However, under scenarios B1 and B2, emissions from the region are expected to decline to 532 Gg/y and 626 Gg/y respectively.

Table 8 Key global attributes of selected IPCC scenarios (Streets, 2007)

Scenario	Description	1996			2030			2050		
		Population, 10^6	GDP, $US/cap	Coal use, EJ	Population, 10^6	GDP, $US/cap	Coal use, EJ	Population, 10^6	GDP, $US/cap	Coal use, EJ
A1B	A future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies	5789	5017	93.2	8190	12,277	185.3	8716	24,239	234.1
A2	A very heterogeneous world, based on self-reliance and preservation of local identities. Population growth is high. Per capita economic growth and technological change are more fragmented and slower than in other scenarios	5799	5007	93.2	9254	6959	167.9	11,309	8564	255.2
B1	A convergent world with low population growth but rapid change in economic structure toward a service and information economy. There are reductions in material intensity and the introduction of clean and efficient technologies	5789	5017	93.3	8,190	10,600	110.0	8716	18,361	118.8
B2	A world in which the emphasis is on local solutions to economic, social and environmental sustainability. A world with moderate population growth, intermediate levels of economic development, and less rapid technological change	5784	5021	93.2	8384	9393	144.7	9386	13,637	124.2

The projections for 2050 show a decline in BC emissions from South Asia under all four scenarios, with the greatest reduction, down to 406 Gg/y, being achieved under scenario B1. The B1 scenario was associated with the most significant decline in emissions from the residential combustion sector, representing the replacement of traditional fossil-fuel and biofuel stoves in the developing world with higher grade fuels and more advanced technologies such as cook stoves.

Emissions from the transport sector were predicted to continued to increase in the near-term future but control technologies are expected to have improved by 2050. The banning of open-field burning by 2050 was also considered to be an important factor in reducing future global emissions.

Streets (2007) carried this work on further to identify world regions and economic sectors which could be targeted for aerosol reduction. The largest reductions can be achieved in the household combustion sector with the replacement of inefficient stoves burning low grade fuels. Streets goes as far as to say that 'overall, the outlook seems bright for reduced worldwide emissions from the household sector in the future'. For the industrial sector, reductions are likely due to actions and regulations already in place and the likely continuation of this trend. The only region with significant additional potential for reduction in BC emissions from the industrial sector is East Asia and this will require action against poorly controlled coal-fired facilities, especially in China.

For the transport sector, Streets (2007) notes that the trends in emissions from the transport sector are more complex. Although emissions are being reduced by improved technologies and control in the developed world, this is not the case in developing regions, which may see increased emissions in the near-term future. Biomass burning emissions are expected to decline due to increasing urbanisation and a spreading awareness of the adverse effects of this practice.

The transport sector is a significant source of BC emissions in India and is by far the greatest source of air pollution in Indian cities. Total particulate emissions from gasoline amounted to 10 kt in 1998 whereas emissions from diesel consumption were almost an order of magnitude greater at 86 kt. Emissions of particulate matter from the transport sector almost doubled between 1990 and 1998 and this increase is likely to continue well into the 21st century (Mitra and Sharma, 2002).

It is interesting to note that the BC emissions to the Arctic region are predicted to decrease by 41% compared to 2005 levels by 2030, not as a result of any direct actions against sources of BC emissions but rather due to stronger PM controls on diesel vehicles. Further, the majority of these emission reductions will be as a result of changes in the transport sector – other sectors may remain constant or even increase. Globally, BC emissions are predicted to fall by 10–20% between 2005 and 2030, with continued reductions after that date. However, this decrease will not be evenly distributed and some areas may even see an increase during this period (Arctic Council, 2011).

Cofala and others (2007) estimated global air pollutant emissions to 2030. Baseline emissions were estimated assuming current expectations of economic development and on the implementation only of legislation which was already in place. For this, the GAINS model data were used. The study concentrated only on emissions from intentional human activities, excluding emissions from deforestation, savanna burning and vegetation fires. As shown in Figure 1, emissions of BC have been relatively stable, with a slight decline in emissions from domestic combustion, between 1990 (5.5 Tg/y) and 2000 (5.3 Tg/y), despite an increase in emissions from the transport sector. Total emissions are expected to decline slightly (17%) by 2030 under the CLE (current legislation and economic development) scenario. Should maximum technically feasible reductions (MFR, applying state of the art control technologies to all sources) be applied, the emission reductions could be quite significant (50-60% below 2000 levels), especially in the industrial and transport sectors. However, even with these MFR approaches, emissions from the domestic sector do not decline significantly and remain as the dominant source of BC emissions beyond 2030.

Looking more closely at regional emissions, Cofala and others (2007) estimated that emissions from

South Asia (excluding Pacific and centrally planned Asia), amounted to 0.7 Tg/y in 1990 and 0.8 Tg/y in 2000. This was predicted to return to 0.7 Tg/y under the CLE scenario but could be halved to 0.4 Tg/y under the MFR scenario. The largest reductions are reported to be possible in the transport sector, small-scale residential combustion and through a ban on open burning of crop residues. Cofala and others (2007) predicted that many of the traditional cooking appliances will remain in use up to 2030.

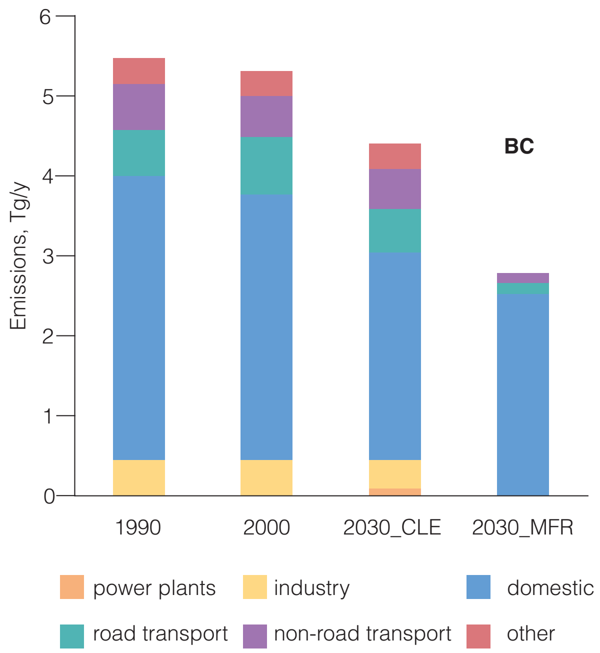

Figure 1 Projected development of global anthropogenic BC emissions by economic sector – estimates for 1990 and 2000 and for 2030 for the 'current legislation' and 'maximum technically feasible reductions' cases (Cofala and others, 2007)

As always, these emission estimates have large associated uncertainties, up to a factor of four to five for the BC estimates, with the largest uncertainties originating from diesel use and wood combustion (Cofala and others, 2007).

Klimont and others (2009) provide information on the emission factors for India for the baseline scenario (mg/MJ) for different sectors in the future, as shown in Table 9. These changes are based on the uptake of control technologies. Legislation for residential combustion is expected to be minimal and therefore the emission factors do not change much. The emission factors for diesel and gasoline road transport, however, are expected to decline significantly by 2030 due to control requirements and increased efficiencies.

As was discussed in Chapter 2, the GAINS model has been used as the basis for many inventories and predictions. The GAINS

Table 9 Impact of air quality legislation – change in implied emission factors for India in the GAINS baseline scenario, mg/MJ (Klimont and others, 2009)

Sector	Fuel	2000	2005	2010	2020	2030
Black carbon						
Residential combustion	coal	130	130	130	129	129
	biomass	85	84	84	84	83
Road transport	heavy duty trucks – diesel	33	31	26	6	6
	cars – diesel	72	69	60	18	17
	cars – gasoline	6	6	6	3	3
Organic carbon						
Residential combustion	coal	200	200	197	187	168
	biomass	231	229	225	218	211
Road transport	heavy duty trucks – diesel	20	19	16	3	3
	cars – diesel	26	25	21	4	3
	cars – gasoline	19	18	16	3	2

baseline predictions for BC for India were shown in Table 4. Whilst emissions from combustion for energy, production processes, waste treatment and disposal, and agriculture were expected to remain constant or decline, emissions from residential combustion, combustion in the manufacturing industry and off-road transport were expected to increase. This, however, represents baseline data for the GAINS database and therefore does not take into account any changes in legislation, rather assuming a business-as-usual increase in emissions with growth in population and continued industrialisation.

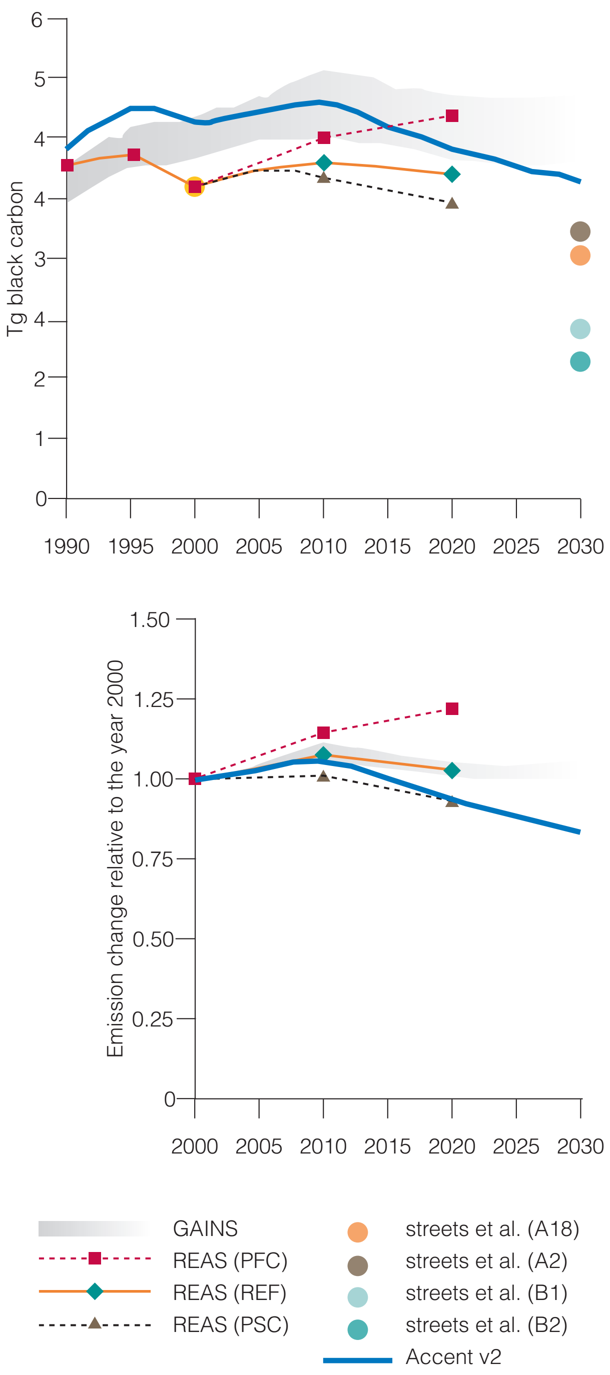

Figure 2 Comparison of BC emission estimates for Asia and their growth rates from the year 2000 (Klimont and others, 2009)

Klimont at others (2009) used the GAINS database to estimate emissions of BC for Asia for 1990-2005 and then provided estimates for 2010-30. Emissions of BC are expected to peak between 2005 and 2010 and then steadily decline. Figure 2 shows estimates from various studies cited collated by Klimont and others and shows the general agreement that emissions are currently peaking and a future decline is likely. The extent of the decline could be anywhere between moderate (10–20%) to significant (>50%) by 2030. The latter estimate assumes virtual elimination of residential coal use in China and significant reduction of biofuels in Asia. Growing demand for energy in the domestic sector in India is likely to be met by centralised heat and power and similar sources which emit 'far less' particles. As can be seen in Table 9, the efficiency of the combustion sources does not change, rather there is a change in fuel use structure in the residential sector. Klimont and others (2009) note that any action taken to accelerate the replacement of low efficiency combustion devices would help reduce emissions faster.

Rypdal and others (2009) continued the work of Cofala and others (2007) and Klimont and others (2009) and added in the issue of economics. Centrally planned Asia and South Asia are the regions where BC controls are most plentiful and cost-effective. The transport sector will not be an area where reduction in emissions can be achieved without incurring significant expense. However, reductions in emissions from industry could be relatively cheap. This will result as a combination of efficiency improvements, fuel switching and end-of-pipe control technologies.

Marginal abatement cost curves (MAC) were developed for each global region based on the MFR scenario mentioned earlier. The MAC identified the cost of abating one additional unit of BC with the addition of each approach or control technology (such as wet scrubbers) and expressed the results in terms of €/t BC abated. The data used for such calculations were, by default, based on values and costs for the EU and North America but were extrapolated as much as possible to represent costs in other global regions. For example, costs for control technologies for coal-fired plants in South Asia were based upon costs reported for the Ukraine and Russian Federation. The MAC were then analysed to divide the abatement costs into quartiles, the first quartile representing those actions which would achieve the greatest reduction in BC emissions at lowest cost. Centrally Planned Asia (CPA) and South Asia (SAS) dominated this quartile, suggesting they offer the cheapest and most plentiful options.

Rypdal and others (2009) went on to propose mitigation scenarios to compare costs. The three scenarios can be summarised as follows:

S1 Maximising reductions in radiative forcing only – the implementation of reductions to achieve the greatest reduction in the radiative forcing of BC. This takes into account region-specific global warming potentials. Cost-effectiveness is ignored in this scenario;

S2 Cost-effectiveness – based on the results of the MAC analysis discussed above, this scenario assumes that actions are taken to target BC where the results will be most cost-effective (such as from industrial and domestic sources in CPA and SAS);

S3 Ability to pay – GDP is used as a proxy for the ability to pay to determine where action is most likely to be taken to reduce emissions.

The scenarios were then applied to the target of reducing the global radiative forcing of BC by 10% and 20%. Within this, the results were further divided into three categories:

GWP only	Where only the direct global warming potential of each pollutant is considered;
Total GWP	Where the total global warming was considered -taking secondary effects into account;
Efficacy	Where climate effects are weighted to take into account the higher climate efficacy of BC deposited on snow and ice.

The results for CPA and SAS are shown in Table 10. The results for the EU are included for comparison.

The S1 scenario, maximising reductions on BC radiative forcing only, is only really relevant in South Asia as this is where the issue is most pressing. This also results in the greatest costs since it requires the specific targeting of large numbers of distinct sources in this region. Under the S3 scenario, regions such as CPA are unable to afford to invest in control measures and therefore emissions increase significantly. The most interesting results are those for the S2 scenario, the most cost-effective reduction strategy, where the indication is to target sources in Asia first – to attain the 10% reduction in RF (direct GWP only) then 50% of the global effort should be applied in CPA and 18% in SAS. For a 20% radiative forcing (RF) reduction, these values increase to 31% and 23% respectively.

The study goes on to suggest that to achieve the 20% RF reduction (globally) under the S2 scenario, that is in the most cost-effective manner, the majority of BC reduction (37%) should take place in the road transport/machinery sector followed by industrial processes and domestic boilers. However, for the 10% RF target, the largest share (56%) should take place in industrial processes as this sector is regarded as having a large mitigation potential and many low-cost control measures available.

The study by Rypdal and others (2009) is complex and detailed and the interested reader is recommended to study the original paper. However, there are several clear and distinct conclusions which are highlighted:

- the optimal strategy from a climate change and total global cost perspective is to prioritise abatement of BC emissions in Asia;
- reducing BC emissions in Asia would achieve the highest co-benefit reduction in PM_{10} emissions.

Table 10 Regional emission reductions (kt/y) and local annual costs (billion €) for selected regions under 10 and 20% reduction in BC radiative forcing (Rypdal and others, 2009)

Scenario	10% reduction in BC radiative forcing				20% reduction in BC radiative forcing			
	BC	OC	PM10	Costs	BC	OC	PM10	Costs
EU-17								
Direct GWP only								
S1	0	0	0	0	0	0	0	0
S2	5	2	17	0	27	9	64	1
S3	38	13	96	2	43	21	173	4
Total GWP								
S1	0	0	0	0	0	0	0	0
S2	5	2	17	0	27	9	65	1
S3	39	14	97	3	43	21	173	4
Efficacy								
S1	0	0	0	0	48	48	243	19
S2	5	2	17	0	28	9	66	1
S3	39	14	97	3	44	21	173	5
CPA								
Direct GWP only								
S1	0	0	0	0	0	0	0	0
S2	199	164	650	0	242	188	2060	2
S3	210	174	1040	1	321	230	18873	9
Total GWP								
S1	0	0	0	0	0	0	0	0
S2	199	164	650	0	240	188	1925	2
S3	209	173	969	1	321	230	18873	9
Efficacy								
S1	0	0	0	0	0	0	0	0
S2	197	164	619	0	240	188	1916	2
S3	208	170	833	1	308	228	18853	8
SAS								
Direct GWP only								
S1	137	138	5559	3	224	174	6495	24
S2	74	69	1066	1	182	149	5470	7
S3	16	12	178	0	99	111	2765	2
Total GWP								
S1	137	138	5559	3	224	174	6495	24
S2	76	98	2328	1	182	149	5443	7
S3	16	12	178	0	99	111	2765	2
Efficacy								
S1	226	201	7380	24	226	201	7380	24
S2	72	96	2320	1	182	150	5476	7
S3	18	24	766	0	98	111	2622	2

3.3 Comments

The population in India is growing rapidly and this comes with associated economic and industrial development. Despite this, it would seem that most studies predict that emissions of BC globally, and in India specifically, are unlikely to grow significantly in future and may actually decline under some scenarios.

Declining global BC emissions are predicted to result from changes in fuel use as well as improvements in technology and emissions control. The reduction or banning of open-field burning of agricultural wastes will go a long way to reducing BC emissions.

Reducing emissions from residential combustion is a significant challenge – reductions in emissions will only result via a change in human behaviour and common cooking practices throughout India and most authors believe that this will not happen quickly. However, Streets (2007) goes so far as to say that 'overall, the outlook seems bright for reduced worldwide emissions from the household sector in future'. Much of the reduction in emissions from residential cookstoves will result from the increased provision of power (electricity and piped gas) to regions which currently rely on local biomass. However, any action to accelerate the replacement of low efficiency combustion devices will help reduce emissions faster.

Emissions from industry should reduce in future as older plants come offline and are replaced by more efficient systems. The transport sector could achieve reductions over several decades but this will require a step-wise change in fuel and vehicle type and this will not happen without incurring significant expense.

4 Pathways to reduction

Rypdal and others (2009) looked at the cost-effectiveness of global BC abatement strategies. They suggest that prioritising emission reductions in Asia is the best option for three reasons:

1 Asia is responsible for a large share of total emissions;
2 the region has lower abatement costs compared to Europe and North America;
3 the region would see significant co-benefit reductions due to reduced PM_{10} emissions.

In Chapter 3 it was shown that BC emissions both globally and in Asia are likely to stabilise and even decline in future. However, this rate of decline will be dependent on the actions taken to control or limit BC emissions from the different regions and sectors. This chapter concentrates on discussing those options which will be most appropriate for guaranteeing and even accelerating the reduction BC emissions in India.

4.1 Targets for reduction

UNEP, in conjunction with WHO, have produced a summary of the BC and ozone issues for decision makers (UNEP, 2011). The report provides a simple discussion of the benefits of emission reductions on the environment along with a list of proposed measures. The proposed measures are summarised in Table 12 (*see* Section 4.2). These options concentrate on actions largely in the domestic combustion and transport sector. Achieving reductions in these sectors requires a complete change in the way the population travel and go about their daily lives and will therefore require a significant amount of time, effort and funding to be successful. Assuming these measures are applied globally to reduce both emissions of CH_4 and BC, just under 0.5 °C of warming could be avoided, around 2.5 million premature deaths could be averted and crop yields of over 50 Mt year could be saved.

The UNEP (2011) report considered different policy options for estimating emissions to 2030, based on 2005 emissions, as follows:

- reference scenario : based on IEA predictions for fuel use and current policies;
- CH_4 measures : including the CH_4 options listed in Table 11;
- BC measures: including the BC options listed in Table 11;
- CH_4 + BC measures : including both CH_4 and BC measures in Table 11;
- CO_2 measures : including additional actions against CO_2;
- CO_2 + CH_4 + BC : a combination of all of the above.

Figure 3 shows the potential for changes in total emissions to 2030 based on the different scenarios. The potential for reductions in BC emissions could be as much as almost 80%, with the majority of reduction being achieved in emissions from residential and commercial combustion as well as transport. It is interesting to note from Figure 3 that the measures applied to reduce BC emissions would also achieve significant reductions in all of the other short-lived climate forcing pollutants. It is therefore clear that actions to reduce BC emissions will have far more impact on the global climate than simply that from BC reduction alone and would also have a substantial affect on health and climate in Asia. The emission reductions predicted could also affect the Asian monsoon, mitigating disruption of traditional rainfall patterns. However, the models are not robust enough to give a clear indication of possible local climatic effects.

Anenberg and others (2011) have also estimated the impacts of reducing BC emissions in various regions and sectors on air quality and human mortality. Results, based on a combination of models and emission inventories (data from the year 2000), suggest that halving global BC emissions from human activities would lead to the avoidance of 157,000 premature deaths per year globally. Most of these deaths would be avoided in East Asia (China, 54%) and South Asia (India, 31%). Halving

Table 11 Measures that improve climate change mitigation and air quality and have a large emissions reduction potential (UNEP, 2011)

Sector	Measure
CH_4	
Extraction and transport of fossil fuel	Extended pre-mine gasification and recovery and oxidation of CH_4 from ventilation air in coal mines Extended recovery and utilisation, rather than venting, of associated gas and improved control of unintended fugitive emissions from the production of oilf and natural gas Reduced leakage from long-distance pipelines
Waste management	Separation and treatment of biodegradable municipal waste through recycling, composting and anaerobic digestion as well as landfill gas collection with combustion/utilisation Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control
Agriculture	Control of CH_4 emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs Intermittent aeration of continuously flooded rice paddies
BC measures (affecting BC and other co-emitted compounds)	
Transport	Diesel particle filters for road and off-road vehicles Elimination of high-emitting vehicles in road and off-road transport
Residential	Replacing coal by coal briquettes in cooking and heating stoves Pellet stoves and boilers, using fuel made from recycled wood waste of sawdust, to replace current wood-burning technologies in the residential sector in industrialised countries Introduction of clean-burning biomass stoves for cooking and heating in developing countries Substitution of clean-burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries
Industry	Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries
Agriculture	Ban on open-field burning of agricultural waste

emissions from residential combustion would lead 47% of the mortality reduction, industrial emissions to 35% and transportation emissions to 15% under this scenario. Biofuel combustion causes eight times more premature deaths globally than fossil fuel combustion, largely due to the use of biofuel in areas of greater and denser populations.

As mentioned by Quinn and others (2008), specific source regions must be targeted to lessen the impacts of short-lived pollutants such as BC. The authors also suggest that targeting sources that emit aerosols with a high absorptivity and relatively low reflectance would also mean a more significant reduction for every tonne of BC reduced. Appropriate sources would be diesel combustion and residential stoves.

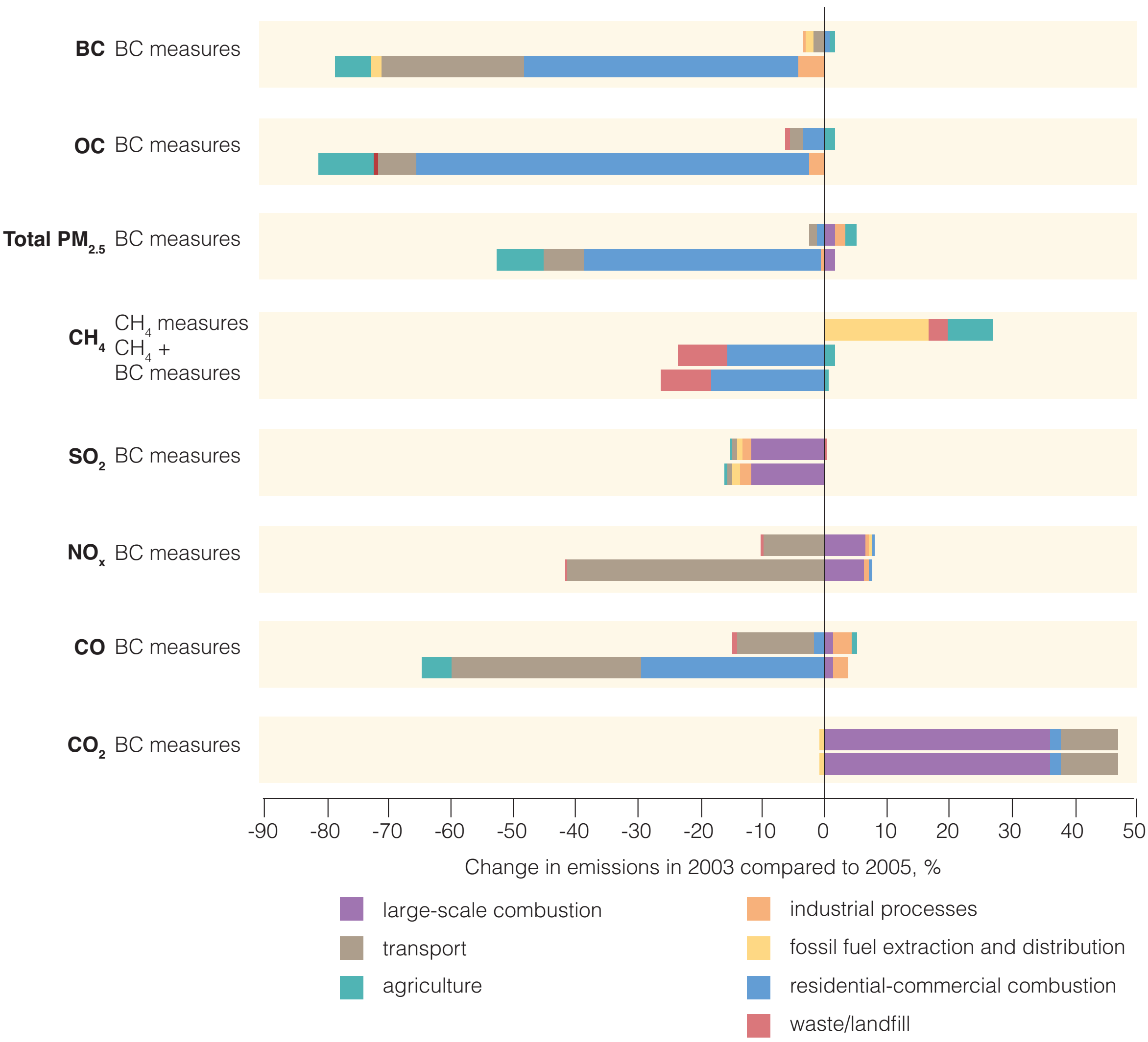

Figure 3 Percentage change in anthropogenic emissions of the indicated pollutants in 2030 relative to 2005 for reference scenarios (UNEP, 2011

In their assessment, the Arctic Council (2011) listed the key mitigation measures relevant to emissions from Scandinavia, and North America. These are:

Transport	Diesel particle filters and elimination of high-emitting vehicles (old and inefficient)
Domestic	Replacing coal with briquettes in cooking and heating stoves
	Recycled wood pellet stoves to replace wood-burning stove
	Introduction of clean-burning biomass stoves for cooking and heating in developing countries
	Substitution of clean burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries
	Regular maintenance of oil-fired residential boilers
Industry	Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns
	Replacing traditional coke ovens with cleaner options
	End-of-pipe options for PM controls
	Regular maintenance of oil-fired industrial boilers
Agriculture	Ban on open-field burning of agricultural waste

Since BC is a constituent of total particulates, it can be assumed that controls to reduce emissions of particulates would reduce emissions of BC. However, the effects of these controls are not always proportionate (Arctic Council, 2011).

The Arctic Council (2011) listed means by which BC emissions could be reduced. These included targeting the following areas:

- the transport sector – for example retirement of older vehicles, upgrading of equipment, accelerated implementation of low-sulphur diesel;
- the domestic heating sector – for example tighter standards on emissions, certification schemes for stoves, increased efficiency;
- open biomass burning – for example assistance to the agriculture sector to encourage non-burn methods, fire-management programmes;
- marine shipping (more specific to the Arctic region) – technical and operation methods to reduce BC emissions from shipping activities;
- gas flaring – more data collection and information on best practices.

The following sections briefly discuss the priorities for action in each of the major BC sectors**.**

4.1.1 Power production

Although not currently a major source of BC emissions in India, the growth in the power sector in India will be significant. This increase in available power will mean the spread of electrification through previous remote and rural areas of India and will mean that many households currently relying on biomass for cooking will be able move away from this, reducing emissions from the residential sector.

The increase in coal combustion for power generation is unlikely to cause a significant increase in BC emissions from this sector – the emission factor for BC is low for this sector as combustion is relatively efficient and BC emissions are low. Further, particulate control systems are effective in capturing most particulate emissions. However, some work should be invested in monitoring emissions to ensure that these particulate control devices are being operated correctly.

4.1.2 Industry

Somewhat dated industries such as brick kilns are a significant source of particulate pollution and these are still popular in India (Rypdal and others, 2009). However, there are means of improving the operation of these systems to reduce emissions. Efficiency projects in Mexico have improved small brick kiln efficiencies by 50% and reduced particulate emissions by 80%. Similarly, a project in Vietnam has demonstrated the use of limestone scrubbing systems on brick kilns to reduce emissions. Projects such as this could be tested in India and promoted as much as possible (UNEP, 2011).

In addition to cleaning up the existing plants, projects could be initiate to promote the move towards more modern, efficient industries with lower fuel intake and lower emissions of all pollutants.

Reducing emissions from industrial sources requires investment. Reductions are therefore unlikely to happen without incentives such as either legislative requirements or funding. Demonstration projects should be established in India, similar to those in Mexico and Vietnam, to allow local plant operators to understand that relatively small investments in changes in operation can result in significant improvements in plant performance, working conditions and even process economics.

4.1.3 Transport

The transport sector is a significant source of BC emissions in India and is by far the greatest source of air pollution in Indian cities. Reducing emissions from this sector is a challenge as the majority of sources are privately owned and not currently subject to any emission legislation. Reducing emissions will therefore be a relatively long-term process which should involve changes in the performance and efficiency of future vehicles and, if possible, either the removal or upgrade of older vehicles. Sources which are government owned or owned by private industry may be easier to tackle. For example, in Santiago diesel particle filters (DPF) have been installed on one third of the urban buses. New York and London have also required DPFs to be installed on city bus fleets. DPFs have been required on all new diesel passenger cars in the UK since 2006-07. However, the use of DPFs requires greater availability of low sulphur diesel which will require a step-change in the country fuel supply and distribution systems (UNEP, 2011). The local population will buy the cars and fuel available to them – changing emissions from this sector will therefore involve significant involvement at the government level to ensure a move towards cleaner fuels and cleaner vehicles. The move will require significant investment at the governmental level and costs will undoubtably pass on to the public in increased vehicle and fuel costs.

4.1.4 Residential

Residential combustion in India is by far the greatest target area for reduction but may also be the most difficult sector to target. Rural and remote communities have no alternative but to use low-grade biomass fuels for cooking. Even kerosene and paraffin used for cooking can cause significant health effects. Moving populations away from this practice will require providing them with a feasible alternative. This will include:

- the continued electrification of the country and the improved distribution of centrally produced power;
- promotion of alternative cooking equipment – the replacement of inefficient cookstoves to more efficient alternatives. This is likely to require some sort of extensive promotional and incentive-based programme as it will require a change in human habit and behaviour in these regions. Cheap and simple alternatives must be made available that will be considered either as good as (simple and cheap) or better than the systems currently in place;
- increased availability of leaner burning fuels such as briquettes or natural gas.

4.2 Partnerships and action plans

There are numerous activities under way in Asia to reduce emissions of pollutants. For example, there are already several partnership working within Asia to improve air quality. These are summarised in Table 12. It would be wise for any new activities to take these existing activities into account and, where possible, operate in a synergistic manner to maximise results.

India currently has a well-developed network of ambient monitoring stations at over 290 sites throughout India. The majority of these are fitted with rain and sunlight measurement systems, although some (around 61 sites in cities in 1996) also have pollution monitoring equipment for species such as total particulate matter, SO_2 and NOx for which national ambient air quality standards (NAAQS) apply (Mitra and Sharma, 2002).

The Indian Ministry for the Environment and Forests (MEFGI, 2011) introduced a Black Carbon Research Initiative in 2011 which aims to establish a scientific network and knowledge base for BC study in India. The launch report acknowledges the lack of data on Indian BC, regarding many of the transport model predictions for India as ‘unrealistic’. The initiative aims to involve over 100 institutes with 60 observatories throughout the country. The study would lead to:

- long-term monitoring of aerosols;
- monitoring of the impact of BC on snow;
- estimating the magnitude of BC sources using inventory (bottom-up) and inverse modelling (top-down) approaches;
- modelling BC atmospheric transport and climate impact.

Table 12 Examples of Asian air quality partnerships (Rono and others, 2011)

Partnership	Regional Scope	Year	Focus
Clean Air Initiative for Asian Cities (CAI-Asia) Secretariat: CAI-Asia Centre	Asia	2007	Partnership of organisations promoting better air quality aiming at policies and actions to reduce air pollution and GHG emissions from transport, energy and other sectors.
Co-benefits Partnership Secretariat: IGES	Asia	2010	Partnership of organisations to improve knowledge management and stakeholder cooperation of co-benefits in Asia
Project Atmospheric Brown Cloud (ABC) Secretariat: UNEP	Asia	2002	Partnership of national environment agencies focused on atmospheric BC as an emerging regional climate change issue in Asia
Malé Declaration Secretariat: UNEP	South Asia	1988	Intergovernmental cooperation of South Asian countries aimed at the control and prevention of air pollution and its likely transboundary effects for South Asia
Global Atmospheric Pollution Forum (GAP) Secretariat: Stockholm Environment Institute	Global	2004	Partnership of organisations aimed at developing effective policies and programs to protect public health and the environment from the harmful effects of atmospheric pollution
Partnership on Sustainable Low Carbon Transport Secretariat: UN DESA	Global	2009	Partnership of organisations to reduce the growth of GHG emissions generated by land transport in developing countries by promoting more sustainable, low-carbon transport

This ambitious project would be run under the auspices of the Indian Network for Climate Change Assessment (INCCA). The planned projects include BC network measurements from both aircraft-based studies and multi-satellite analysis, combining these into a regional BC model which would then contribute to a radiation and climate model to provide an impact assessment.

The MEFGI (2011) study gives maps of where sampling stations would be located throughout the country and gives details of the measurement technologies which would be used along with a list of the 101 institutes and organisations which will take part in the initiative.

The US EPA (US Environmental Protection Agency) has established a five-year cook stove research initiative looking at reducing BC exposure and how to reduce this (US EPA, 2011). The results of this study will indicate the most efficient systems available which could be provided as alternatives to the existing systems used at the moment.

The Indian National Cookstove Initiative (NCI, initiated in 2009) aims to work towards moving the entire cooking population of India (160 million households) from using inefficient stoves firing biomass, wood and coal to more efficient cookstoves which can run as cleanly as LPG-fired systems. This initiative, although still in relatively early stages, could reduce Indian BC emissions by up to one third, avoid over 570,000 premature deaths and reduce 4% of Indian's greenhouse gas emissions (Venkataraman and others, 2010).

4.3 Comments

The challenge of reducing BC emissions in India is not an insignificant one. However, it would seem that the literature is unanimous in its suggestions for priority areas for action and these are:

residential fuel use > transport > industry > other (including power production)

The means to reduce emissions from these sectors are all fairly well established. The challenge will be putting them into place in such a large and growing population as India. However, there are projects and partnerships in place which should be leveraged to maximise the potential for change.

5 Recommendations

Perhaps one of the major conclusions from a literature search on BC emissions in India is the general lack of published data and that even the published data tend to be acknowledged as incomplete or inaccurate due to the lack of monitoring in the sectors which are known to be amongst the largest emitters – domestic and industrial combustion. There are numerous papers modelling the effects of BC emissions and possible future scenarios but all of these acknowledge that the assumptions made are based on limited data. Clearly there is much investment needed on measurement and monitoring emissions of BC to establish more region and sector-appropriate emission factors and to keep up with, in some cases, more accurate data on activity data on rapidly increasing fuel use. Despite this, there is no doubt that India is a major source of BC and that this BC is directly associated with many negative environmental effects. Reduction of BC is therefore an obvious target.

The following sections summarise the major issues raised by this report along with the most obvious priorities for action.

Benefits of BC reductions

1. Reducing emissions of BC will result in reduced global warming effects, reduced glacier melt, increased crop production, reduced negative health effects and many other both global and regional effects.
2. Reducing emissions of BC will have knock-on beneficial effects in reduction of emissions of other pollutants such as fine particulates.
3. Many of the approaches taken to reduce BC emissions, such as fuel changes, process optimisation and emission control and changes in cooking habits, are all actions that will improve resource management and sustainability, making industry more cost effective and improving the general quality of life for millions.

Gaps in data and scientific knowledge

1. There is a mismatch between values for BC emissions produced by bottom-up emission inventories and values obtained from atmospheric measurement and monitoring. More needs to be done to determine why this occurs and how it should be corrected. A mismatch between emission data and environmental measurements implies either errors in calculations or errors in the understanding of the behaviour of BC in the atmosphere, both of which need to be addressed.
2. Spatially resolved maps of emissions are available and these should be used more actively to determine regional areas which would be most appropriate for immediate action.
3. Many BC reduction strategies will be strategies which reduce emissions of all particulates. However, this may not necessarily guarantee a proportionate reduction in BC emissions. Sectors and strategies which will guarantee the most effective BC reductions should be identified more clearly.
4. Reductions in BC emissions will result in both regional and global environmental changes in climate and atmospheric chemistry. It is possible that reductions in emissions from certain sectors could be more effective in reducing some climatic effects than others. For example, reductions in aerosols with high absorptivity and relatively low reflectance would also mean a more significant reduction for every tonne of BC reduced. This would include sources such as diesel combustion and residential stoves. Clarifying the extent of this effect will give a better indication of more appropriate target strategies.
5. India has recently announced its intention to establish a BC study programme under the auspices of the INCCA which will involve over 100 national organisations and research body and expand upon the monitoring network system already in place in the country. This project is ambitious and could benefit from international support.

Priorities for action:

- Power generation – although not a significant source, emissions from this rapidly growing sector should be monitored to ensure that plants are operating efficiently and pollution control devices are working correctly.
- Industry – most industrial units in India have on-site combustion systems to provide power and are using low grade coals for this. Emission reductions can be achieved by closing down these plants and moving to more centralised energy production. When this is not possible, changes in fuel use to higher grade, cleaner burning fuels and combustion systems and the application of end-of-pipe cleaning technologies will be beneficial. Older systems such as brick kilns must either be modernised or replaced completely.
- Transport – changes in vehicle use happens over shorter periods of time than changes in power production or industry. However, improvements in the vehicle sector will require a step-change in fuel supply to cleaner fuels and also a step-change in vehicle types to more efficient vehicles and vehicles installed with emission controls. These changes are likely to require significant changes at the government level which will make it either compulsory or economically beneficial for commercial industry to offer cleaner fuels and cleaner vehicles. This will require significant investment.
- Residential – significant changes in habits and lifestyles are required. Those who have used the same cookstoves and fuels for years are unlikely to make a change to more efficient systems without either a legal requirement or some form of incentive. This could be free replacement or part-exchange of old devices with new, cleaner fuels should be made readily available and cheap. Initiatives already under way in India, such as the NCI should be encouraged and assisted in their activities.

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