

On the future of carbonaceous aerosol emissions

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[1] This paper presents the first model-based forecasts of future emissions of the primary carbonaceous aerosols, black carbon (BC) and organic carbon (OC). The forecasts build on a recent 1996 inventory of emissions that contains detailed fuel, technology, sector, and world-region specifications. The forecasts are driven by four IPCC scenarios, A1B, A2, B1, and B2, out to 2030 and 2050, incorporating not only changing patterns of fuel use but also technology development. Emissions from both energy generation and open biomass burning are included. We project that global BC emissions will decline from 8.0 Tg in 1996 to 5.3–7.3 Tg by 2030 and to 4.3–6.1 Tg by 2050, across the range of scenarios. We project that OC emissions will decline from 34 Tg in 1996 to 24–30 Tg by 2030 and to 21–28 Tg by 2050. The introduction of advanced technology with lower emission rates, as well as a shift away from the use of traditional solid fuels in the residential sector, more than offsets the increased combustion of fossil fuels worldwide. Environmental pressures and a diminishing demand for new agricultural land lead to a slow decline in the amount of open biomass burning. Although emissions of BC and OC are generally expected to decline around the world, some regions, particularly South America, northern Africa, the Middle East, South Asia, Southeast Asia, and Oceania, show increasing emissions in several scenarios. Particularly difficult to control are BC emissions from the transport sector, which increase under most scenarios. We expect that the BC/OC emission ratio for energy sources will rise from 0.5 to as much as 0.8, signifying a shift toward net warming of the climate system due to carbonaceous aerosols. When biomass burning is included, however, the BC/OC emission ratios are for the most part invariant across scenarios at about 0.2. *INDEX TERMS*: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; *KEYWORDS*: aerosols, emissions, projections, global, black carbon, organic carbon

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1. Introduction

[2] Carbonaceous aerosols consist of fine particles, mostly less than 1 micrometer (μm) in diameter, which are usually classified as either black carbon (BC), essentially but not identically the same as elemental carbon (EC) [Bond *et al.*, 1998], or organic carbon (OC), in which the carbon is bonded to other elements. The role of aerosols in modifying the earth's climate has been known for many years [see, e.g., Charlson *et al.*, 1992; Kiehl and Briegleb, 1993; Schwartz, 1996; Schwartz and Andreae, 1996; Kiehl, 1999]. In recent years, the importance of carbonaceous aerosols to global radiative forcing has been stressed in a

number of important papers and commentaries [Hansen *et al.*, 2000; Hansen and Sato, 2001; Andreae, 2001; Penner *et al.*, 2001; Jacobson, 2001, 2002; Chameides and Bergin, 2002]. BC has been proposed as possibly the second most important greenhouse species after CO_2 [Hansen *et al.*, 2000; Jacobson, 2001, 2002] with a positive net radiative forcing of as much as 0.5 W m^{-2} , though that view has been challenged by Penner *et al.* [2003].

[3] The ability of carbonaceous aerosols to modify local meteorology and climatology in regions where emissions are high, like China and India, has been postulated [Ackerman *et al.*, 2000; Ramanathan *et al.*, 2001a, 2001b; Lelieveld *et al.*, 2001; Menon *et al.*, 2002]. Carbonaceous aerosols have been the subject of a number of regional and global modeling studies aimed at linking source distributions with ambient concentrations and light absorption measurements through the simulation of atmospheric transport, chemistry, and removal—and ultimately evaluating their effects on radiative forcing and climate change [Liousse *et al.*, 1996; Chameides *et al.*, 1999, 2002; Tegen *et al.*, 2000; Koch, 2001; Chin *et al.*, 2002, 2003; Cooke *et al.*, 2002; Menon *et al.*, 2002; Hansen *et al.*, 2002;

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Jacobson, 2002; Chung and Seinfeld, 2002; Kinne et al., 2003; Wang, 2004; Reddy and Boucher, 2004].

[4] All the models used in these studies require as input some representation of the strength and spatial distribution of primary emissions. The development of a reliable data set of emissions of global carbonaceous aerosols, however, has not been easy; and the inventories in use today are flawed. Section 2 reviews the development of emission inventories of carbonaceous aerosols, culminating in the recent inventory of Bond et al. [2004] upon which this paper is founded; this review highlights the level of confidence that we have in various aspects of carbonaceous aerosol inventories. Because of the importance of carbonaceous aerosols to radiative forcing, a reliable present-day emission inventory is necessary for the application of regional atmospheric chemistry models and general circulation models to studies of the current state of the atmosphere and climate.

[5] Also of importance is the need to develop estimates of likely emissions of carbonaceous aerosols in the future, so that we can forecast future climate change and evaluate the effects of possible mitigation options. Thus far, such estimates have not been made in a rigorous way. The IPCC Third Assessment Report [IPCC, 2001] generated a wealth of projections of future emissions of greenhouse gases [Nakicenovic et al., 2000]; and from the forecasts of SO₂ emissions it was also possible to develop scenarios of sulfate aerosol formation, which were used extensively in global modeling. But very little information on primary carbonaceous aerosol emissions was provided by the IPCC. For the modeling of future climate in the IPCC Third Assessment Report, future emissions of BC and OC were developed simply by scaling the available present-day inventories with CO emission forecasts (see Table 5.7, footnote b, and Appendices II.1.9 and II.1.10 in IPCC [2001]). This is an unsatisfactory approach because of the different factors influencing future emissions of fine particles and CO, particularly the ability to control particle emissions at reasonable cost and the societal imperative of reducing human health effects due to fine particle inhalation. We have developed a model-based approach for forecasting BC and OC emissions, and we present in this paper results for 2030 and 2050 for the four major IPCC scenarios. This is the first time that rigorous forecasts of primary carbonaceous aerosol emissions have been reported, and thus we complete the set of emissions needed to model future climate under different assumptions and consistent with the available projections of other chemical species.

2. Emission Inventory Development

[6] Early attempts to estimate emissions of carbonaceous aerosols were rudimentary and yielded highly uncertain results. Turco et al. [1983] and Ghan and Penner [1992] tentatively placed annual, global BC emissions in the range of 2–12 Tg. Then, in a seminal paper, Penner et al. [1993] derived the first reliable BC emission estimates. By studying the ratios of BC to “smoke” and SO₂ measurements, they proposed that BC emissions could be inferred from observed BC/S ratios in different parts of the world. A global annual emission value of 23.8 Tg was obtained by this method. A second method presented in the same paper,

based on rather crude BC emission factors and the global use of diesel fuel, coal, wood, and bagasse, yielded an estimate of 12.6 Tg for the year 1980. Biomass burning from land clearing was estimated to produce a further 5.7 Tg. Lioussé et al. [1996] modified and extended the work of Penner et al. [1993] to yield estimates of 6.6 Tg for fossil-fuel use and 5.6 Tg for biomass burning of all kinds.

[7] In 1996 the first paper was published that estimated global BC emissions using specific emission factors and disaggregated fuel use applied to a wide variety of source types [Cooke and Wilson, 1996]. Their estimates were 8.0 Tg from fossil-fuel combustion and 6.0 Tg from biomass burning. Two drawbacks to this work were that it was based on old (1984) fuel use data and omitted biofuel combustion, which is known to be a big contributor to global BC emissions. However, most significantly, Cooke and Wilson used inappropriate emission factors for large sources such as coal-fired power plants and industrial boilers, failing to appreciate that the bulk of fine particle emissions from such sources is not carbonaceous but mineral in nature. An update of this paper was published [Cooke et al., 1999], in which the estimate of fossil-fuel BC emissions was reduced to 6.4 Tg for bulk BC (BC particles of all sizes) and 5.1 Tg for submicron BC (only BC particles <1 μm in diameter). Many deficiencies of the original work remained. The inventories of Penner et al. [1993], Cooke and Wilson [1996], and Cooke et al. [1999] have been the sources of emissions for most of the modeling studies cited previously. Köhler et al. [2001] developed a global inventory of BC emissions from road traffic (2.4 Tg for 1993), partly based on Cooke and Wilson [1996].

[8] Despite uncertainties in the magnitude of BC emissions, one thing was clear from this early work: China and India generate a sizeable proportion of global BC emissions, due to the widespread and often uncontrolled burning of coal and biofuels; Chameides and Bergin [2002] showed that these two countries together produce fully 25% of global BC emissions. In order to gain a better perspective on BC emissions in China, Streets et al. [2001a] conducted a detailed investigation of technologies and fuels, part of which consisted of a thorough review and assessment of the literature on fine particle emissions by combustion experts. Through this process, a more robust set of emission factors was developed for the various source types, coordinated with available measurements of PM_{2.5} and PM₁₀ emission factors and appropriate submicron and carbonaceous fractions. The paper stressed the high uncertainty associated with BC emission factors, due to the wide variety of combustion conditions found in different types of combustors. Streets et al. [2001a] estimated that the residential burning of coal in a traditional stove has a BC emission factor of 3.7 g kg⁻¹ (central value). In contrast, the BC emission factor for a large coal-fired boiler using an electrostatic precipitator is only about 0.0001 g kg⁻¹. Emissions are low for large boilers because the very high temperatures and efficient mixing of air and fuel readily oxidize any fine carbon particles leaving the combustion zone; it is primarily mineral matter that escapes and is either captured in the particulate control device or passes through into the atmosphere. This latter value is in sharp contrast to the value of 1 g kg⁻¹ chosen by Cooke and Wilson [1996] for industrial coal combustion (including power plants). The

estimate of BC emissions in China by *Streets et al.* [2001a] was 1.3 Tg for 1995, consisting of 0.8 Tg from fossil-fuel combustion and a large contribution (0.5 Tg) from biofuel burning. *Cooke and Wilson* [1996] estimated BC emissions in China in 1984 to be 1.1 Tg from fossil fuels alone. These two results are inconsistent, if only because coal consumption in China increased by 83% between 1984 and 1995.

[9] A new Asian emission inventory for the year 2000 [*Streets et al.*, 2003a, 2003b] was developed for the NASA TRACE-P program [*Jacob et al.*, 2003] and the NSF/NOAA ACE-Asia program [*Huebert et al.*, 2003]. This inventory included estimates of Asian BC and OC emissions based on the emission factors of *Streets et al.* [2001a]. It was estimated that Asian BC emissions in 2000 were 2.5 Tg, of which China generated 1.1 Tg and India 0.6 Tg. The decline in China's BC emissions from 1.3 Tg in 1995 to 1.1 Tg in 2000 is believed to be real and is attributed to a decline in coal consumption after 1996, associated with the Asian economic recession, industrial restructuring, fuel switching in the residential sector, and efficiency improvements [*Streets et al.*, 2001b].

[10] The final step in this process to date has been the extension of the China and Asian emissions work to a new global inventory [*Bond et al.*, 2004], which applied emission factors updated from *Streets et al.* [2001a] to 1996 global fuel use at the national level [*IEA*, 1998a, 1998b] in more than 100 sector/fuel/technology categories. Global BC emissions according to this new inventory are 8.0 Tg in total (consisting of 3.0 Tg from fossil-fuel combustion, 1.7 Tg from biofuel combustion, and 3.3 Tg from open biomass burning). This estimate is significantly lower than previous estimates. The increase in fuel use between the early 1980s and the mid-1990s is insufficient to offset the decrease in the emission estimate caused by lowering the emission factors of large stationary sources. *Bond et al.* [2004] present a detailed analysis of the differences between the new inventory and its predecessors.

[11] Several pieces of supporting evidence for the new BC emission values have emerged from recent inventory, modeling, and measurement programs. The European BC source strength has been inferred from a four-year period of measurements of ambient BC concentrations taken at the Mace Head Baseline Atmospheric Research Station on the Atlantic coast of Ireland [*Derwent et al.*, 2001]. Using back-trajectory analysis and Lagrangian dispersion modeling to identify sampled air masses that originated in regionally polluted Europe, a value of 482–511 (± 140) Gg for annual European BC emissions was estimated, which is in reasonable agreement with the value of 510 Gg in the inventory of *Bond et al.* [2004].

[12] *Park et al.* [2003] inferred an estimate for U.S. EC emissions of 750 Gg from modeling and measurement integration based on a priori estimates from *Cooke et al.* [1999] and other sources. This is higher than the *Bond et al.* [2004] inventory value of 410 Gg, but within the uncertainty range and influenced by the higher a priori value used. Also for the United States, a preliminary BC emissions inventory developed for the U.S. EPA has an estimate of 430 Gg, based on the U.S. 1999 National Emission Inventory V2 [*Battye and Boyer*, 2002]. For the transport sector, *Battye and Boyer* [2002] calculate BC emissions in 1996 to be about 220 Gg, which compares well with the

Bond et al. [2004] value of 200 Gg. More importantly for these projections, future BC emissions from transport in the U.S. are projected by the U.S. EPA to fall to about 135 Gg in 2030 without additional control measures and to be constrained to about 90 Gg in 2030 by new particulate regulations for on-road and non-road diesel vehicles [*DeAngelo et al.*, 2003]. These values are in good agreement with our projections that are driven by technology performance rather than regulatory prescription: 85–125 Gg across the four scenarios for 2030. In the sense that advances in technology are driving the adoption of tighter regulations good agreement is perhaps not surprising.

[13] The magnitude of Asian BC emissions was also probed during the TRACE-P [*Jacob et al.*, 2003] and ACE-Asia [*Huebert et al.*, 2003] field campaigns of April 2001. *Matsumoto et al.* [2003] reported measurements of elemental carbon at four ground stations during ACE-Asia. The network consists of Japanese island stations (Rishiri, Sado, Hachijo, and Chichi-jima) stretching along the line of 140°E latitude from 25°N to 45°N and thus ideally suited to study a cross-section of the particle flux swept off the Chinese coast. *Uno et al.* [2003] modeled the transport of BC using the CFORS model with the TRACE-P emission inventory [*Streets et al.*, 2003a, 2003b] and obtained good agreement for both absolute concentration levels and time variation of the concentrations. Occasionally at Sado there was an underprediction when the prevailing wind came from the main Japan islands. This suggested that local Japanese sources were partly responsible, and the authors speculated that the burning of agricultural residues in the field prior to rice planting might have been the cause. *Carmichael et al.* [2003] also showed reasonable agreement for the entire set of TRACE-P observations at altitudes below 1 km, in which the average modeled BC concentration was $0.67 \mu\text{g m}^{-3}$ compared with the observed average of $0.84 \mu\text{g m}^{-3}$.

[14] Analysis of BC aircraft observations during TRACE-P by *Clarke et al.* [2004] showed generally good agreement between measured absorption and modeled BC concentrations using the TRACE-P emission inventory. This was particularly true of aged air masses originating in Southeast Asia and western China. Averages of observations grouped in $0.1 \mu\text{g m}^{-3}$ bins fit well within the expected bounds of $6\text{--}10 \text{ m}^2 \text{ g}^{-1}$ BC. However, for air masses sampled close to the Chinese coast, there was a significant difference between measured and modeled BC concentrations (which were very high on these flights), suggesting an underestimation of BC emissions by a factor of 2–3. This is similar to the situation with TRACE-P observations of CO, which were sometimes 1–2 times higher than predicted values in air masses sampled in the Yellow Sea. *Huebert et al.* [2003] pointed out that BC/CO ratios were actually well predicted, so this can help in the identification of any sources likely to be underestimated in the inventory.

[15] There is also some doubt about the magnitude and sources of Indian BC emissions. *Streets et al.* [2003a] estimated BC emissions in India to be 600 Gg, though this value is even more uncertain than the estimate for China because of doubts about the emission factors of Indian vehicles, the degree of fuel adulteration in Indian vehicles, and emission factors for dung-burning cookstoves. *Reddy and Venkataraman* [2002a, 2002b] estimated Indian BC

emissions to be 380 Gg for 1998–99, using a similar approach and emission factors. However, *Dickerson et al.* [2002] expressed the belief that BC emissions could be considerably higher, possibly as high as 2–3 Tg, based on atmospheric measurements taken during INDOEX, especially the observed BC/CO ratios. In addition, the primary source of the BC is in dispute. *Novakov et al.* [2000] asserted that fossil-fuel combustion was the primary source, based on interpretation of the chemical profiles of sampled aerosol. *Mayol-Bracero et al.* [2002] suggested that 60–80% was from fossil fuel and 20–40% from biofuel. However, this seems unlikely because the primary carbonaceous emissions from coal-fired plants in India are largely controlled; biofuel combustion in the residential sector is a more likely cause. The finding of chemically mixed submicron particles containing carbon and potassium, a tracer for vegetation burning, seems to be supportive [*Guazzotti et al.*, 2003]. *Guazzotti et al.* infer 74% biofuel/biomass contribution to submicron carbonaceous aerosol. Open biomass burning in India has been shown to be extremely uncertain [*Streets et al.*, 2003b] with estimates varying by an order of magnitude. This uncertainty, coupled with the seasonal variability of open burning, makes it extremely difficult to pinpoint source contributions.

[16] Global emissions of OC were first estimated by *Lioussé et al.* [1996] to be about 62 Tg (organic matter emissions of 81 Tg divided by 1.3). Biomass burning contributed 34 Tg, fossil-fuel combustion 22 Tg, and natural sources 6 Tg. The *Lioussé et al.* estimate for combustion emissions was based on assumed OC/BC ratios, not direct measurements, and attempted to account for secondary aerosol production. Subsequently, *Cooke et al.* [1999] derived primary emission values of 10.1 Tg bulk OC and 7.0 Tg submicron OC from fossil-fuel combustion, though the same caveats apply as to their BC estimates. In a later modeling study, *Cooke et al.* [2002] doubled their emission estimate to 14 Tg submicron OC, presumably to account for secondary formation of OC. The OC estimates by *Bond et al.* [2004] for 1996 are 2.4 Tg from the combustion of fossil fuels, 5.8 Tg from the combustion of biofuels and 25 Tg from open biomass burning, for a total of 33 Tg; these authors have not attempted to account for secondary OC formation.

[17] Though many uncertainties still remain, particularly for BC emissions from China and India, we believe we are approaching a reasonable level of understanding of global emissions of primary BC and OC. Studies are underway to test the *Bond et al.* [2004] emission estimates against currently available field observations; and we expect that iteration among emissions, atmospheric measurements, model results, and combustion tests will result in improved understanding of the present-day magnitude of carbonaceous aerosol emissions. Now, because of the significant contribution of carbonaceous aerosols to radiative forcing, a critical question arises for assessing global climate change in the 21st century: How are emissions of carbonaceous aerosols likely to change in the future?

3. Forecasting Approach

[18] The basic approach taken in this paper is to project the 1996 inventory of *Bond et al.* [2004] to the years 2030

and 2050 using growth scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). In similar previous work, we developed 2030 global forecasts of gaseous species important for the formation of ozone [*Fiore et al.*, 2002], including NO_x, CO, CH₄, and speciated VOC. Regional growth rates were developed by source category and world region between 1995 and 2030 for the IPCC A1B and B1 scenarios. Results showed that reducing global CH₄ emissions was a powerful lever for reducing high O₃ events in the United States under the A1B scenario. That study further indicated that changing patterns of global emissions around the world in the future can markedly influence ambient air concentrations locally through intercontinental transport. Similar forecasts of future tropospheric ozone concentrations using IPCC growth factors were developed by *Prather et al.* [2003] and of radiative forcing due to changes in tropospheric and stratospheric ozone by *Gauss et al.* [2003].

[19] Projecting emissions of BC and OC presents particularly difficult problems not encountered for gaseous species. First, the majority of global emissions arise from source types and in geographical areas for which data are of limited availability and reliability. Second, the emission rate for a particular sector/fuel combination is greatly dependent on the type of combustion technology used, and few statistics are available on the partitioning of sector/fuel combinations among various technologies. Third, particulate controls of various types and performance characteristics are already in widespread use around the world and they are also poorly known, although they have critically important effects on particulate emissions. These matters have been studied in our previous work concerned with present-day characteristics of energy use and carbonaceous aerosol emissions [*Streets et al.*, 2001a; *Bond et al.*, 2004]; however, if characterization of present practices is difficult, then projecting how they will change in the future is an even greater challenge. Nevertheless, we strongly believe that a technology-based approach is necessary in order to obtain reasonable projections of future BC and OC emissions, particularly for intermediate-term projections, such as the ones presented here. If technology is the strongest determinant of carbonaceous aerosol emissions today, then technology changes over time will govern the magnitude of future emissions.

[20] Because the forecasts presented in this paper are based on IPCC projections, the first step is to transform the national emission estimates of *Bond et al.* [2004] to IPCC world regions. We chose to use the IPCC forecasts developed by the IMAGE group at the National Institute for Public Health and the Environment (RIVM) in the Netherlands [*RIVM*, 2001]. In the IMAGE work, information is presented for 17 major world regions. This level of spatial aggregation strikes a reasonable balance between the national-level information available for current years and the four world regions used in the official IPCC publications [*Nakicenovic et al.*, 2000; *IPCC*, 2001].

[21] Table 1 presents the *Bond et al.* [2004] inventory of global BC emissions for the five major source sectors transformed to IPCC world regions. A small discrepancy of ~1% is introduced in the process of aggregating data in the model from national level to world-region level. It is clear that biomass burning generates the majority of BC

Table 1. Breakdown of 1996 Global BC Emissions^a

World Region	Residential	Industry	Power	Transport	Biomass Burning	Total
Canada	8	13	0	20	52	93
United States	79	66	6	203	61	414
Central America	29	24	1	55	105	214
South America	51	60	0	149	802	1063
Northern Africa	24	18	0	19	3	64
Western Africa	186	21	0	12	675	894
Eastern Africa	73	2	0	3	242	320
Southern Africa	92	14	0	23	545	675
OECD Europe	47	67	3	226	50	392
Eastern Europe	64	26	1	41	6	137
Former USSR	60	51	3	71	98	282
Middle East	22	20	2	118	10	172
South Asia	386	94	1	109	126	715
East Asia	849	511	4	165	132	1661
Southeast Asia	185	72	1	121	208	587
Oceania	5	10	0	19	164	198
Japan	4	74	2	72	2	153
World	2162	1142	24	1426	3280	8035

^aUnits are in Gg.

emissions (41%), with residential fuel burning (27%) and transport (18%) contributing significantly. Emissions are concentrated in the developing regions of the world, where the combustion of fossil fuels and biofuels using less-advanced technology and the open burning of vegetation are widespread: East Asia (21%), South America (13%), western Africa (11%), and South Asia (9%). The distribution for OC is different (Table 2). Biomass burning is by far the largest source type (74%), with a significant contribution from the residential sector (18%). Because biomass burning is so dominant for OC emissions, South America (19%), western Africa (17%), and southern Africa (12%) are the largest contributing source regions. Figure 1 shows the global distributions of BC and OC emissions for energy-related combustion and open biomass burning in 1996.

[22] For the projection of future carbonaceous aerosol emissions, we employ four of the scenarios developed by the IPCC for its Third Assessment Report: A1B, A2, B1, and B2, and two future years, 2030 and 2050 [Nakicenovic et al., 2000; IPCC, 2001]. These scenarios specify the energy use and fuel mix associated with alternative future pathways of human development, which can be directly used in the calculation of future emissions. The scenarios also embody different rates of technology development and technology transfer among countries (“isolationist” scenarios have less transfer); and in our treatment of technological improvements in the future, we incorporate the differences among the scenarios, which are not quantified by the IPCC.

[23] The A1B scenario is characterized by very rapid economic growth, low population growth, continuing globalization in its western form, increasing privatization, and the rapid introduction of new and more efficient technologies. The designation “B” in this scenario connotes a balance of energy technologies across all source types, stressing neither fossil nor renewable energy sources. Quantitatively, the A1B scenario in its IMAGE formulation shows a growth in global GDP from US\$29 trillion in 1996 to US\$101 trillion in 2030 and US\$211 trillion in 2050. Global primary energy use increases from 379 EJ in 1996 to 920 EJ in 2030 and 1355 EJ in 2050.

[24] The A2 scenario reflects a heterogeneous world of self-reliance and preservation of local identities. Population growth is high. Economies develop in a regional rather than global framework with lower per capita economic growth than in the other scenarios. Technological change is slow and fragmented. GDP grows to US\$64 trillion in 2030 and US\$97 trillion in 2050, much less than in A1B. Primary energy use grows to 733 EJ in 2030 and 998 EJ in 2050. High population growth, low technology turnover, and regional isolation tend to increase the use of low-technology options, especially in the near term, leading to generally higher emissions than the other scenarios.

[25] The B1 scenario is characterized by high economic growth, low population growth, and continuing globalization, similar to A1B. However, two major differences from A1B are a change in economic structure toward a service and information economy, and an emphasis on global solutions to social and environmental problems, rather than the pursuit of material wealth. Though the introduction of clean and resource-efficient technologies is stressed under the B1 scenario, technology turnover is not as rapid as the economically driven technology substitution of the A1B scenario. Global GDP grows to US\$87 trillion in 2030 and US\$160 trillion in 2050. Primary energy use grows to 655 EJ in 2030 and 792 EJ in 2050, both significantly less than under A1B.

[26] Finally, the B2 scenario describes a future world in which the emphasis is on local solutions to economic, social, and environmental problems. Population growth and economic growth are moderate. There is less rapid and more diverse technological change than in A1B and B1. Environmental protection and social equity are stressed, but at regional scale rather than global. GDP grows to US\$79 trillion in 2030 and US\$128 trillion in 2050. Primary energy use grows to 722 EJ in 2030 and 860 EJ in 2050.

[27] The scenarios developed for the Third Assessment Report of the IPCC [Nakicenovic et al., 2000; IPCC, 2001] have been criticized on the basis of inappropriate economic assumptions [Castles and Henderson, 2003]. However, the IPCC methodology and assumptions were subsequently defended by their proponents [Nakicenovic et al., 2003].

Table 2. Breakdown of 1996 Global OC Emissions^a

World Region	Residential	Industry	Power	Transport	Biomass Burning	Total
Canada	39	6	0	14	713	772
United States	348	31	10	133	954	1476
Central America	93	61	1	119	801	1075
South America	172	214	1	233	5923	6542
Northern Africa	21	11	0	39	17	89
Western Africa	652	114	0	34	4916	5716
Eastern Africa	262	6	0	4	1655	1927
Southern Africa	263	43	0	51	3910	4267
OECD Europe	172	33	3	97	727	1032
Eastern Europe	231	16	0	22	41	310
Former USSR	153	33	1	37	1405	1629
Middle East	66	12	2	180	60	321
South Asia	1363	230	1	71	756	2420
East Asia	1764	342	1	100	863	3070
Southeast Asia	632	92	1	154	1548	2426
Oceania	13	6	1	9	1129	1157
Japan	3	31	1	32	9	76
World	6246	1281	22	1330	25425	34305

^aUnits are in Gg.

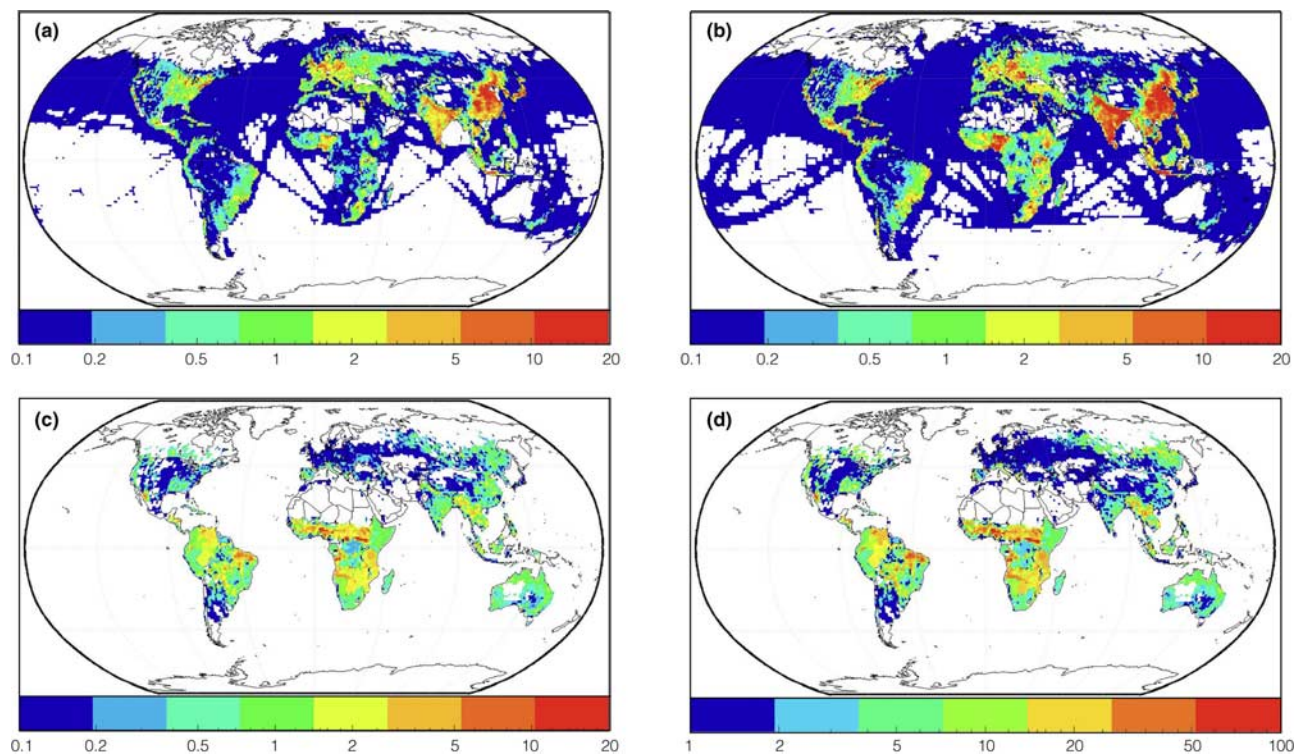


Figure 1. The 1996 emissions ($\text{ng m}^{-2} \text{s}^{-1}$) of carbonaceous aerosols: (a) BC emissions from energy-related combustion; (b) OC emissions from energy-related combustion; (c) BC emissions from open biomass burning; (d) OC emissions from open biomass burning.

In this work, we do not revisit the debate about scenario development. Instead, we simply assume that the chosen IPCC scenarios are reasonable storylines that represent possible future energy pathways, and we project the changes in primary carbonaceous aerosol emissions that would accompany those pathways.

4. Methodology

[28] The calculation of emissions is based on combining fuel consumption data with emission factors, according to the general formulations of Klimont *et al.* [2002] and Bond *et al.* [2004]. The approach is presented schematically in Figure 2. Global emissions under a given scenario i (combination of year and development pathway) of a species j (in this case BC or OC) are given by the sum of calculated emissions for all sector/fuel/technology combinations for all world regions, according to the following equation:

$$Em_{ij} = \sum_k \sum_l \sum_m FC_{i,k,l,m} \left[\sum_n EF_{i,j,k,l,m,n} X_{i,k,l,m,n} \right] \quad (1)$$

where

i, j, k, l, m, n scenario, species, world region, sector, fuel, technology;

Em emissions (g yr^{-1}); FC fuel consumption (kg yr^{-1});

EF emission factor (g kg^{-1} of fuel burned);

X fraction of fuel consumed by a particular technology; note that for a particular sector/fuel combination $\sum_n X = 1$.

[29] In the calculation procedure for 1996, there are 60 combinations of sector (l) and fuel (m) that can be extracted from the IEA fuel use statistics and other data sources (for open biomass burning). However, this breakdown is insufficient for the required calculations of BC and OC emissions, because the technologies used to burn a particular fuel in a particular sector and to collect the particulate matter after initial production have a fundamental bearing on the emission rate. It is for this reason that we further break down the fuel use by technology (n). This further subdivision accounts for the fractional splits by various technology types, including combustors, combustion practices, and particulate matter removal devices. The final list of options contains 112 combinations of sector (l), fuel (m), and technology (n), as listed in Table 3.

[30] Fuel consumption data in the 1996 inventory are taken from energy statistics of the International Energy Agency for the year 1996 [IEA, 1998a, 1998b]. Because the IPCC fuel consumption categories do not exactly match up with the 60 sector/fuel combinations in the 1996 inventory, and because we wish to ensure consistency between the base case and the future projections, we first develop 18 scenario-specific, sector/fuel growth rates from the IMAGE data between the base year (1996) and the future years. These are then applied to the 60 fuel/sector combinations in the 1996 inventory to yield matrices of future fuel consumption:

$$FC_{i,k,l,m} = FC_{1996,k,l,m} \times FCIM_{i,k,l,m} / FCIM_{1996,k,l,m} \quad (2)$$

where $FCIM$ is fuel consumption in the IPCC IMAGE data set.

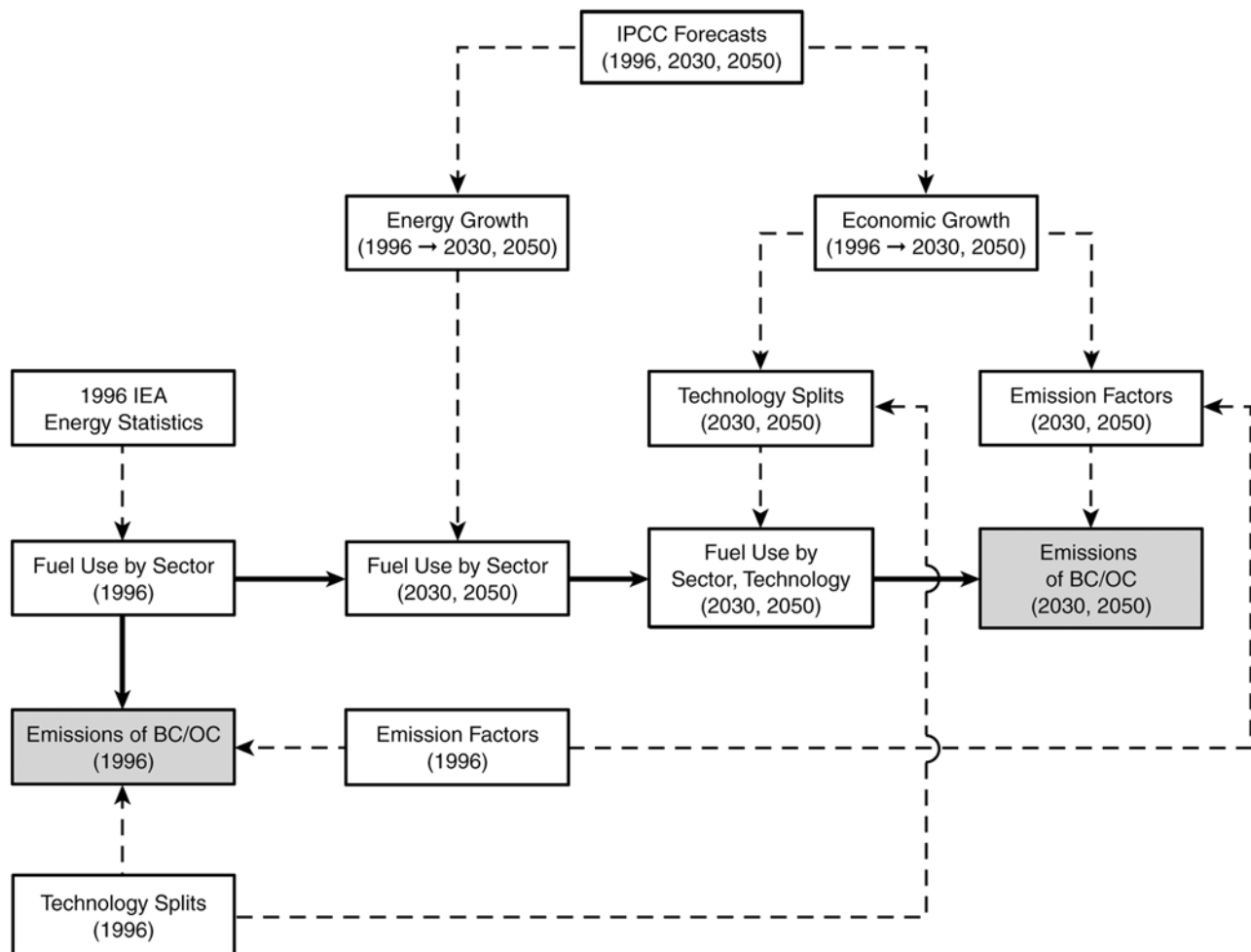


Figure 2. Schematic diagram of forecasting procedure.

[31] It is important to note that major fuel-switching options, for example, from coal to natural gas in the residential sector, are already embodied in the IPCC future scenarios. These are determined by expected fuel-use trends aside from any particular considerations about limiting primary aerosol emissions. Such fuel shifts are incorporated into the baseline of our analysis, and all technology and fuel adjustments discussed in this study in the context of PM control options are relative to the assumptions already contained in the IPCC forecasts. Thus the amount of aerosol reduction caused by switching to cleaner fuels is determined by the IPCC scenarios, while the amount of aerosol reduction caused by using improved technology to burn these same fuels is determined by our analysis.

[32] In the 1996 inventory, the necessary technology splits, $X_{i,k,l,m,n}$ were assembled from many diverse sources for developed countries and by expert judgment for developing countries in situations where no data were available [Bond *et al.*, 2004]. For the future scenarios, we assume that developed countries phase out lower-performing technologies and that developing countries move toward the situation in developed countries; we term this a technology shift, between different rows in Table 3. For the worst performing technologies, which have the greatest bearing on carbonaceous aerosol emissions, we adopt the following approaches

for calculating the technology shift. In the residential sector, traditional cookstoves and open fires fueled by either biofuels or coal are replaced at an annual rate equal to the growth in scenario- and region-specific GDP/capita (1.0–1.8% yr^{-1} in the developed world; 1.9–7.7% yr^{-1} in the developing world). In the industrial sector, traditional bio-fuel industries (using kilns, ovens, etc.) and uncontrolled coal-fired stoker boilers are replaced at an annual rate equal to the growth in scenario- and region-specific industrial value added/capita (0.6–1.7% yr^{-1} in the developed world; 3.1–7.5% yr^{-1} in the developing world). In the present emissions forecasting model, technology shift is not a parameter determined by econometric modeling or supported by historical technology transition rates; in the future we intend to add such linkages to this part of the calculation.

[33] Our earlier papers have discussed some of the difficulties in developing BC and OC emission rates from the available data on particulate mass (PM) emissions [Bond *et al.*, 1998, 2004; Streets *et al.*, 2001a]. Most measurements of PM emissions report total mass, because the important differences in the behavior of PM with different chemical compositions have only recently received attention. Where measured emission factors of black and organic carbon are not available, we have estimated them based on mass emission measurements, usually of PM_{10} or $\text{PM}_{2.5}$,

Table 3. Fuel/Technology Options in Each Major Sector

Fuel	Combustor/Control
<i>Residential</i>	
Agricultural wastes	general
Animal wastes	general
Biofuel	fireplace
Biofuel	heating stove
Biofuel	improved cookstove
Biofuel	open fire
Biofuel	stoker/no control
Biofuel	traditional cookstove
Biofuel	total biomass
Biofuel	charcoal production
Briquettes	general
Brown coal	general
Charcoal	general
Coking coal	general
Diesel fuel	external combustion
Diesel fuel	generator
Hard coal	heating stove
Hard coal	open fire
Hard coal	stoker/cyclone
Hard coal	stoker/no control
Hard coal	traditional cookstove
Heavy fuel oil	general
Kerosene	general
Light distillate oil	general
Liquefied pet gas	general
Natural gas	general
Waste, municipal	general
Waste, municipal	incinerator
Waste, municipal	open fire
<i>Industry</i>	
Biofuel	stoker
Biofuel	stoker/cyclone
Biofuel	traditional industry
Briquettes	stoker/cyclone
Briquettes	stoker/no control
Brown coal	cyclone/filter or ESP
Brown coal	pulverized coal/cyclone
Brown coal	pulverized coal/ESP
Brown coal	pulverized coal/scrubber
Brown coal	stoker/cyclone
Brown coal	stoker/ESP or filter
Brown coal	stoker/no control
Brown coal	stoker/scrubber
Coke oven coke	blast furnace, captured
Coke oven coke	blast furnace, uncaptured
Coking coal	coking, captured
Coking coal	coking, uncaptured
Coking coal	general
Diesel fuel	off-road equipment
Diesel fuel	off-road superemitter
Hard coal	brick kiln
Hard coal	cyclone/cyclone
Hard coal	cyclone/filter or ESP
Hard coal	pulverized coal/cyclone
Hard coal	pulverized coal/ESP
Hard coal	pulverized coal/scrubber
Hard coal	stoker/cyclone
Hard coal	stoker/ESP or filter
Hard coal	stoker/no control
Hard coal	stoker/scrubber
Heavy fuel oil	boiler
Heavy fuel oil	general
Light distillate oil	general
Natural gas	general
Waste, municipal	general
<i>Power</i>	
Biofuel	general
Briquettes	stoker/cyclone
Brown coal	pulverized coal/cyclone
Brown coal	pulverized coal/ESP

Table 3. (continued)

Fuel	Combustor/Control
Brown coal	pulverized coal/scrubber
Brown coal	stoker/cyclone
Brown coal	stoker/ESP or filter
Brown coal	stoker/scrubber
Coking coal	general
Coking coal	stoker/scrubber
Diesel fuel	general
Hard coal	cyclone/cyclone
Hard coal	cyclone/filter or ESP
Hard coal	pulverized coal/cyclone
Hard coal	pulverized coal/ESP
Hard coal	pulverized coal/scrubber
Hard coal	stoker/cyclone
Hard coal	stoker/ESP or filter
Hard coal	stoker/scrubber
Heavy fuel oil	general
Natural gas	general
Waste, municipal	general
<i>Transport</i>	
Aviation gasoline	aircraft
Diesel fuel	superemitter
Diesel fuel	vehicle euro regs
Diesel fuel	vehicle opacity regs
Diesel fuel	general
Diesel fuel	ships
Diesel fuel	tractor
Diesel fuel	tractor superemitter
Diesel fuel	rail
Diesel fuel	international shipping
Hard coal	general
Hard coal	rail
Heavy fuel oil	ships
Heavy fuel oil	general
Heavy fuel oil	international shipping
Light distillate oil	general
Light distillate oil	2-stroke, bad maintenance
Light distillate oil	2-stroke engine
Light distillate oil	superemitter
Light distillate oil	vehicle euro regs
Light distillate oil	vehicle no regs
Natural gas	general
<i>Biomass Burning</i>	
Biomass/open	savanna
Biomass/open	tropical forest
Biomass/open	crop residue
Biomass/open	extratropical forest

combined with data on the submicron and carbonaceous fractions of the emissions, as described in earlier papers. The net emission factor for submicron particles is then given by the equation:

$$EF_{i,j,k,l,m,n} = EFPM_{i,j,k,l,m,n} \times f_{sub_{i,j,k,l,m,n}} \times fC_{i,j,k,l,m,n} \times f_{cont_{i,j,k,l,m,n}} \quad (3)$$

where

$EFPM$ bulk particulate emission factor (usually of $PM_{2.5}$ or PM_{10}) ($g\ kg^{-1}$);

f_{sub} fraction of particles with diameters $<1\ \mu m$;

fC fraction of the particulate matter that is carbon;

f_{cont} fraction of the fine particles that penetrate any control device present.

[34] In practice, not all emission factors vary with region. For example, we have not yet distinguished PM emission factors among world regions for particular sector/fuel/tech-

nology combinations. (Regional differences in net emission rates are represented by different shares of technologies.) Thus, although the model is set up to include all variations, equation (3) is practically implemented in the following way:

$$EF_{i,j,l,m,n} = EFPM_{i,j,l,m,n} \times f_{sub,j,l,m,n} \times f_{C,j,l,m,n} \times f_{cont,i,l,m,n} \quad (4)$$

[35] One of the biggest challenges of this study is the simulation of changes in *EFPM* between 1996 and the future years for a particular sector/fuel/technology combination, i.e., a row in Table 3. We can be sure that technology will not remain stagnant over the 30- to 50-year time period. Gradually, new designs for specific pieces of equipment (e.g., pulverized coal boilers with highly efficient particulate controls for power generation or cookstoves with improved performance) will emerge and take over a portion of the existing population [McDonald and Schrattenholzer, 2002]. These transitions may be driven by economics, technological innovation, environmental regulation, or other factors. In each case, we can assume some decline in *EFPM* over time. (Though current focus on the health effects of fine PM suggests this will be true, it should be noted that some of today's "improved" cookstoves designed to increase energy efficiency actually have higher PM emissions than traditional stoves.)

[36] Our treatment of this issue is to presume that the values of *EFPM* for a future scenario are dependent on (1) the value of *EFPM* today, (2) the likely lowest value of *EFPM* in the distant future, and (3) the likely time period for full transition to the best performing technology under the scenario pathway. Often, we assume that the likely lowest value for a given technology in the distant future will be the "best" performance obtainable today, as defined by the lowest 95th percentile confidence interval of *EFPM* in Bond *et al.* [2004]. Admittedly, this is a simplistic treatment, because some of the spread in observed emission factors results from the normal variability of actual systems. However, because these emission factors are physically achievable today, we assume that innovative methods ranging from fuel processing to improved combustor designs will be found to make them routinely achievable in the future. In some cases, our estimates using this method may underestimate the magnitude of possible emission reductions.

[37] We use the following transformed normal distribution function to estimate 2030 and 2050 *EFPM* values:

$$y = ae^{(-t^2/2s^2)} + b \quad (5)$$

where

- y *EFPM* in the desired future year t (g kg^{-1});
- b best technologically achievable *EFPM* in the asymptotic limit (g kg^{-1});
- $a + b$ *EFPM* in the present day (g kg^{-1});
- s shape parameter for the curve (like the standard deviation).

[38] The use of such s-shaped diffusion patterns to simulate the dynamics of technology innovation is discussed by Grübler *et al.* [1999] in the context of IPCC-like forecasts. By selecting values of the parameters a , b , and s to correspond to the inferred time development pathway of the technology, we can estimate the values of *EFPM* in

2030 and 2050 from equation (5). Also, if the present-day rate of technology penetration is significant (i.e., far from the zero value given by equation (5)), we offset the equation from $t = 0$ to yield a significantly different curve shape. If present production capacity is far lower than that required to begin significant dissemination, we introduce a lag time so that $t = 0$ does not occur for an appropriately specified number of years.

[39] Note that for some sector/fuel/technology combinations, we judge that no improvement is likely in the emission rate between the present and the future, e.g., for low technology like cyclone collectors, which we assume will be simply phased out rather than improved. In other cases, especially when the lifetime of a source type is relatively short (10–20 years), we assume complete transition to a technology type of known emission rate by 2030, obviating the need to use equation (5). These changes are predicated on the basis of past experience with technology innovation and turnover [McDonald and Schrattenholzer, 2002]; however, it does not mean that they will inevitably happen in the absence of external pressure on industry in the forms of government regulation, incentive, or consumer purchasing preference.

[40] Table 4 presents PM emission factors for the twenty major BC source types listed in decreasing order of their contributions to total BC emissions in 1996. The table shows the PM emission factors in 1996 for each of these sector/fuel/technology combinations and the PM emission factors for each of the eight future scenarios resulting from the technology improvement calculations of equation (5). For some source types we show no improvement over time (e.g., traditional cookstoves), which means that rather than upgrading the present technology a shift to improved stoves occurs. In some cases (e.g., wood-fired heating stoves) we project an improvement in performance under the high economic growth scenarios and an additional impulse under the environmental protection scenarios, because improvements (such as catalysts) are available and already required in some regions to improve local air quality.

[41] We assume that f_{sub} and f_C are constant over time for each combination of scenario/species/sector/fuel/technology; i.e., they are independent of $EFPM_{i,j,l,m,n}$. This is probably a source of error, because it is possible that the technology development that spurs the change in *EFPM* will also change the fraction of submicron and carbonaceous particles in the effluent stream. However, because we often do not explicitly know the characteristics of the future technology (it may also be a mix of different technologies), it is difficult to estimate what the changes in f_{sub} and f_C might be. For some technology improvements in the past, f_{sub} has increased, but with the present-day focus on fine particles for health reasons this probably will not be the future trend. We have also simulated improvements in the collection efficiency of particle control technology, f_{cont} , by assuming that the efficiencies of all devices reach the best performance obtained by current technology by 2030. This makes little difference to BC/OC emissions (<0.5%), because collection efficiencies are already high and sources that use particulate collection equipment (large industrial and power generation plants) are small contributors.

[42] For biomass burning, the IPCC forecasts only those emissions that are directly associated with human

Table 4. PM Emission Factors (g kg^{-1}) for the Major BC Source Types in 1996, 2030, and 2050

Sector	Fuel	Combustor Type	Share, ^a %	2030				2050				
				1996	A1B	A2	B1	B2	A1B	A2	B1	B2
Biomass burning	grassland	N/A	21.2	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b
Biomass burning	tropical forest	N/A	12.4	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b
Residential	wood	traditional cookstove	6.2	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Residential	agricultural waste	all	4.8	6.5	6.5	5.7	3.3	3.3	6.5	4.8	3.3	3.3
Biomass burning	crop residues	N/A	4.0	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b
Transport	diesel	superemitting vehicles	3.9	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Transport	diesel	vehicles/opacity regs.	3.3	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Industry	diesel	off-road equipment	3.2	5.5	3.1	3.2	3.1	3.1	3.0	3.0	3.0	3.0
Industry	coking process	uncontrolled	3.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Biomass burning	extratropical forest	N/A	2.9	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b	N/A ^b
Industry	coal	brick kiln	2.6	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Residential	dung cake	all	2.6	3.7	1.9	3.3	1.9	1.9	1.9	2.7	1.9	1.9
Transport	diesel	vehicles/Euro regs.	2.5	1.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Transport	diesel	tractors	2.5	4.0	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0
Residential	coal	open fire	2.2	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Residential	coal	traditional cookstove	2.1	7.7	6.2	6.2	6.2	6.2	4.5	4.5	4.5	4.5
Industry	coking process	controlled	1.8	5.8	2.3	2.7	2.0	2.4	1.8	1.8	1.7	1.8
Residential	wood	heating stove	1.7	15.0	8.8	9.5	7.7	8.8	7.6	8.0	7.5	7.6
Transport	heavy fuel oil	international shipping	1.5	1.8	1.2	1.2	1.2	1.2	1.0	1.0	1.0	1.0
Industry	diesel	off-road superemitter	1.3	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0

^aPercentage contribution of this sector/fuel/technology combination to total BC emissions in the base-year 1996 inventory.

^bFor biomass burning, BC and OC emission factors are used directly from the work of *Andreae and Merlet* [2001], instead of being derived from PM emission factors, and are constant over time.

activities. For example, forest burning is specifically associated with the need to expand agricultural land at the expense of forested land to provide additional food supplies (managed forest in IPCC terminology); because of fluctuating food demand, the amounts of forest burning in the IPCC forecasts also fluctuate dramatically. However, the forecasts do not include the very large contribution from natural wildfires in many parts of the world. For this application, we used the IMAGE managed forest projections directly, but supplemented them with estimates of wildfire emissions using the mature forest projections of the IPCC. A relationship between the total area of forest burned and the resulting emissions was calibrated from the 1996 inventory used in *Bond et al.* [2004],

based on the method of *Streets et al.* [2003b]; and changes in mature forest area over time were assumed to be proportional to changes in wildfire emissions. IPCC projections of grassland and crop residue burning were used directly. These biomass burning projections are not only sensitive to the growth aspects of the scenarios (population and economic), but also to the changing level of environmental awareness vis-à-vis pollution from open burning.

5. Results

[43] The amounts of fuel combusted by sector and fuel type under each scenario are presented in Table 5. These are

Table 5. Global Fuel Combusted (10^9 kg of Fuel) Under Each Scenario

Sector/Fuel	1996	2030A1B	2030A2	2030B1	2030B2	2050A1B	2050A2	2050B1	2050B2
Residential	3543	6354	6043	4737	5873	10576	8265	5743	8161
Biofuel	2378	2276	3080	2335	2299	1995	3289	2066	2181
Coal	349	466	394	277	293	375	758	175	264
Oil	382	1082	769	783	742	1160	967	748	632
Gas	409	2506	1768	1316	2514	7023	3216	2731	5061
Waste	24	24	32	25	24	22	36	23	23
Industry	2587	4909	4160	2860	3708	6306	5627	2844	3578
Biofuel	294	634	461	438	473	624	398	330	346
Coal	1607	2566	2517	1299	1907	3058	3892	1241	1486
Oil	352	710	440	521	510	560	317	303	321
Gas	317	985	730	592	805	2055	1012	964	1416
Waste	15	14	12	10	12	9	9	6	8
Power	3933	15164	10298	10659	12196	31223	17676	17680	20215
Biofuel	66	186	162	148	153	314	259	208	218
Coal	3073	12029	7923	8326	9739	24806	13317	13728	16124
Oil	382	1574	1176	1183	1220	3393	2260	2104	2110
Gas	368	1286	954	931	1007	2589	1730	1558	1672
Waste	43	89	83	70	77	121	110	82	90
Transport	1723	5334	3863	3614	3902	9163	5779	4708	5336
Coal	13	3	5	2	3	8	19	4	6
Oil	1677	4118	2991	3025	2727	4294	3433	2761	2214
Gas	33	1212	867	587	1172	4861	2327	1943	3116
Biomass burning	5985	5275	4793	4483	4820	5682	4255	4434	4145
Total	17770	37036	29156	26352	30499	62950	41601	35410	41435

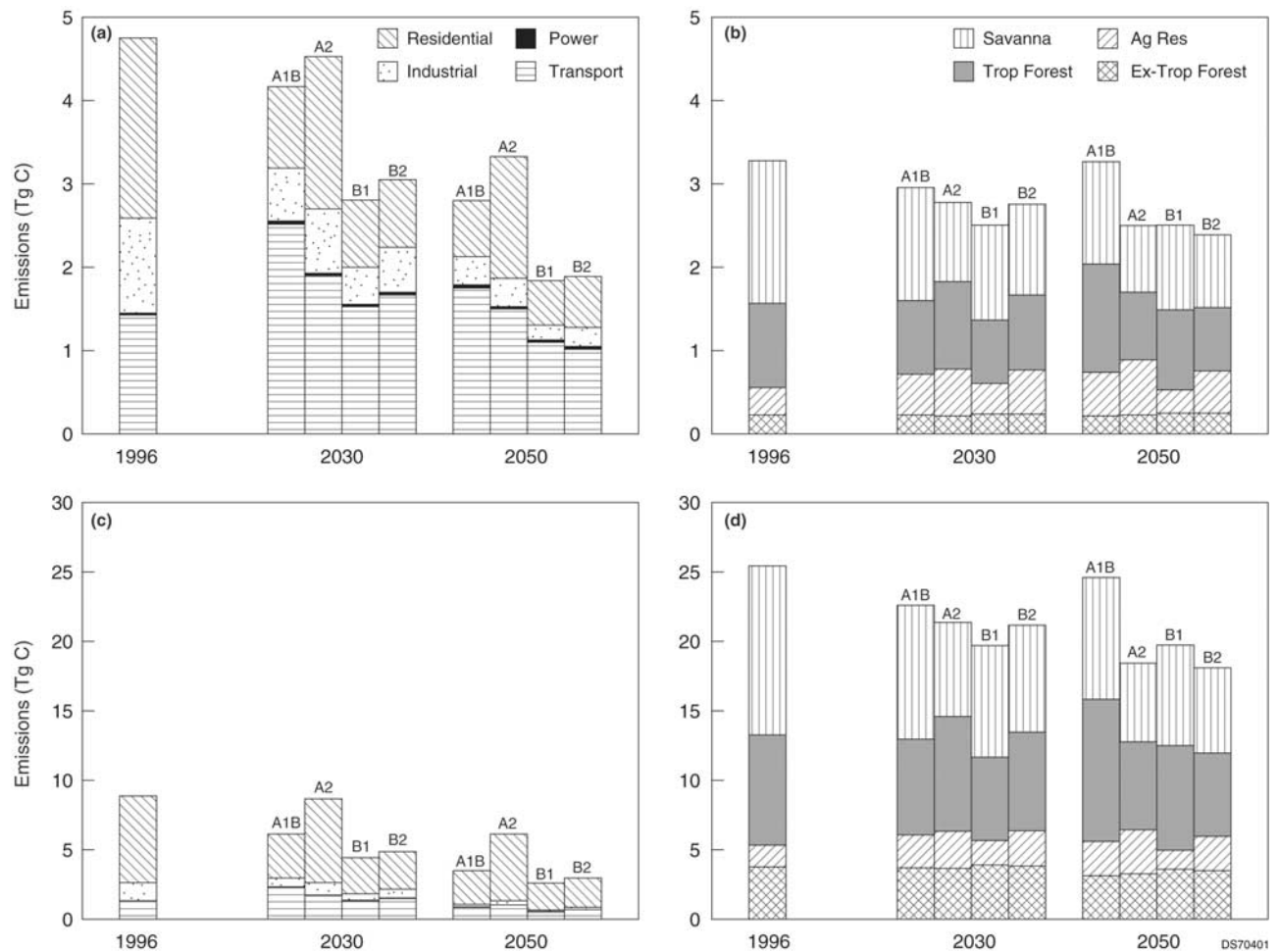


Figure 3. Trends in global carbonaceous aerosol emissions (Tg C): (a) BC emissions from energy-related combustion; (b) BC emissions from open biomass burning; (c) OC emissions from energy-related combustion; (d) OC emissions from open biomass burning.

Table 7. Regional Trends in OC Emissions Under Each Scenario^a

World Region	1996	2030A1B	2030A2	2030B1	2030B2	2050A1B	2050A2	2050B1	2050B2
Canada	772	808	807	785	796	743	749	715	722
United States	1476	1390	1259	1373	1262	1140	1167	1294	1191
Central America	1075	1001	1236	870	706	758	541	813	621
South America	6542	6133	6082	5379	5792	8097	5410	5460	5265
Northern Africa	89	184	180	120	126	85	118	53	64
Western Africa	5716	4357	4877	3485	3597	4249	3207	3180	3351
Eastern Africa	1927	1532	1453	1325	2496	2147	1305	1375	1112
Southern Africa	4267	1871	1187	1703	866	1491	700	1994	542
OECD Europe	1032	840	1101	897	924	752	921	867	898
Eastern Europe	310	244	265	202	213	213	247	204	196
Former USSR	1629	1617	1655	1581	1621	1436	1520	1439	1454
Middle East	321	317	339	207	245	123	308	89	171
South Asia	2420	2158	2618	1568	1609	1718	2215	1158	1349
East Asia	3070	1986	2552	1406	1586	1639	2384	1168	1344
Southeast Asia	2426	2612	2930	1905	1524	1711	2263	1387	1299
Oceania	1157	1646	1487	1330	2651	1770	1499	1123	1492
Japan	76	42	41	31	33	30	28	19	21
World	34305	28737	30069	24166	26048	28103	24584	22340	21094
		<i>Percent Change</i>							
Northern Hemisphere		-15	-5	-29	-25	-25	-24	-38	-38
Southern Hemisphere		-19	-27	-30	-22	-5	-36	-28	-39
World		-16	-12	-30	-24	-18	-28	-35	-39

^aUnits are in Gg.

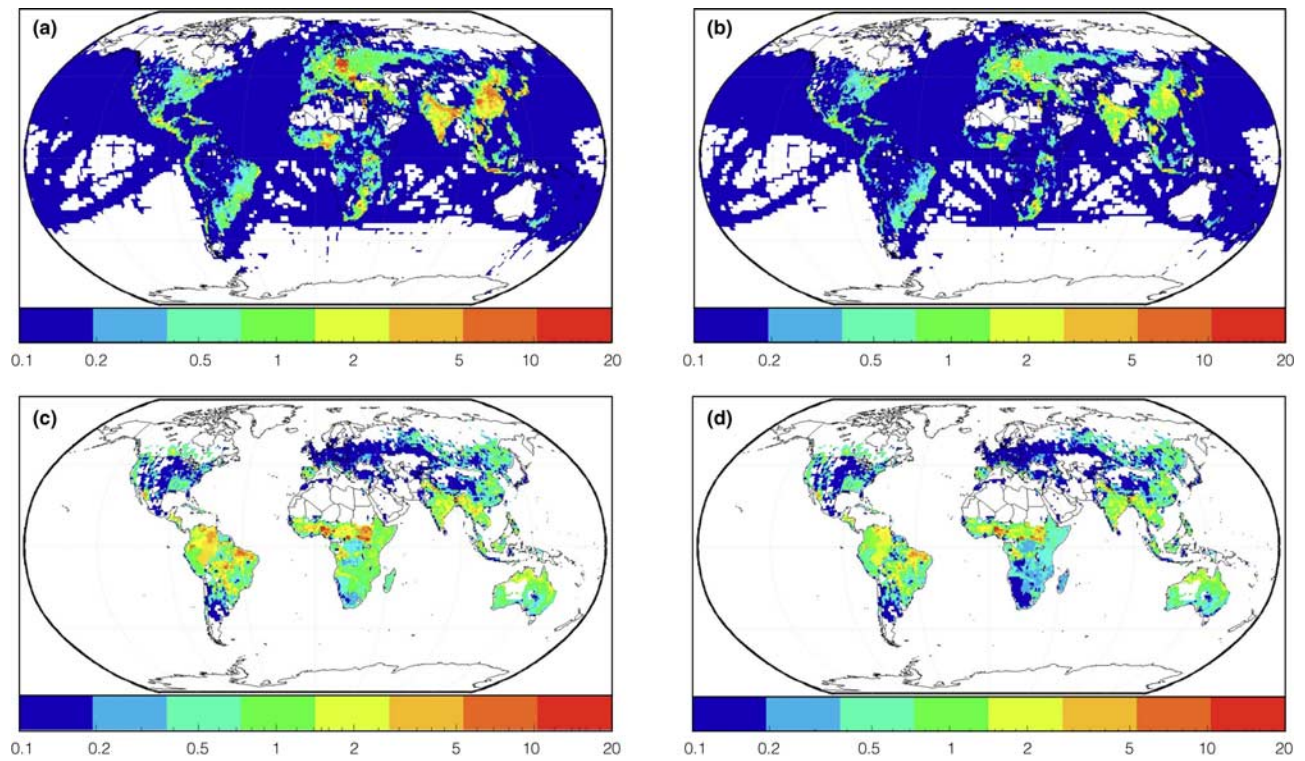


Figure 4. Future BC emissions ($\text{ng m}^{-2} \text{s}^{-1}$): (a) 2050A2/energy-related combustion; (b) 2050B1/energy-related combustion; (c) 2050A1B/open biomass burning; (d) 2050B2/open biomass burning.

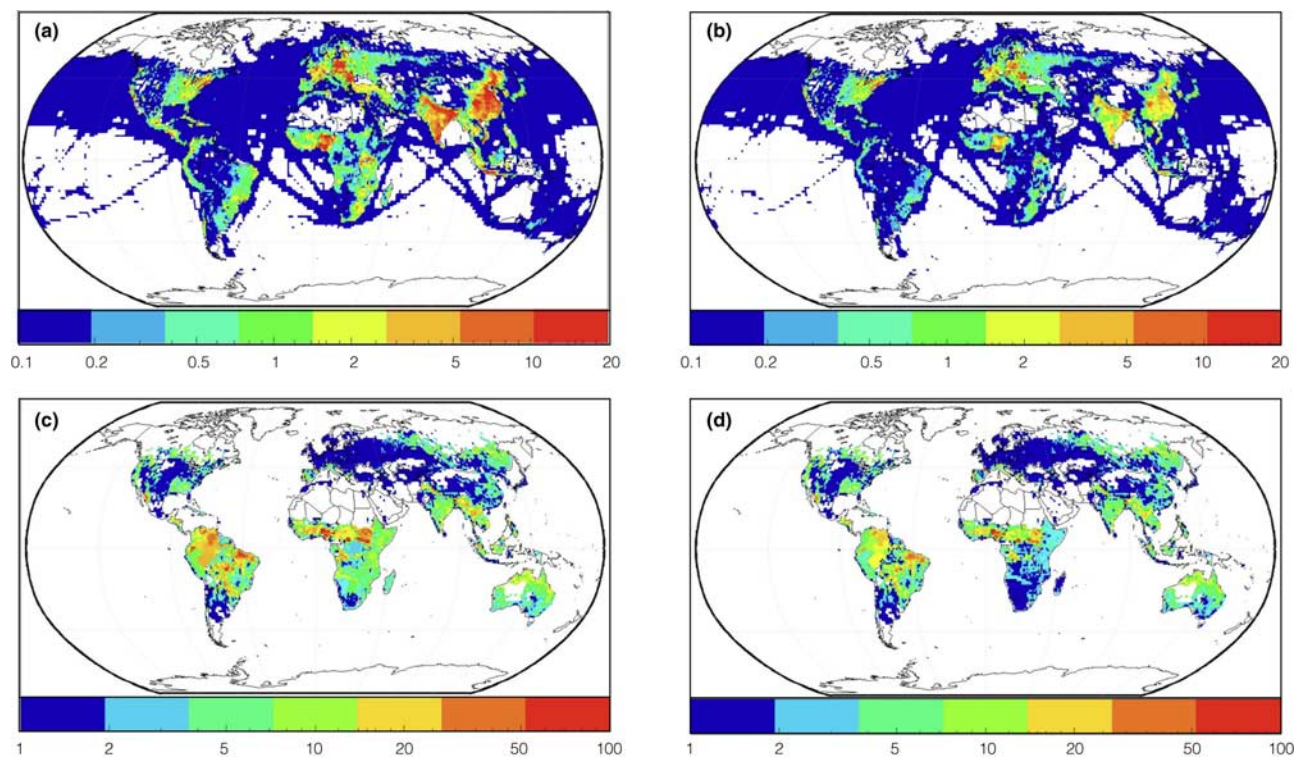


Figure 5. Future OC emissions ($\text{ng m}^{-2} \text{s}^{-1}$): (a) 2050A2/energy-related combustion; (b) 2050B1/energy-related combustion; (c) 2050A1B/open biomass burning; (d) 2050B2/open biomass burning.

Table 8. Sectoral Trends in Global BC and OC Emissions for Each Scenario^a

Sector	1996	2030A1B	2030A2	2030B1	2030B2	2050A1B	2050A2	2050B1	2050B2
BC									
Residential	2162	980	1831	810	814	671	1457	534	612
Industry	1142	625	767	436	537	344	336	176	232
Power	24	36	27	28	28	43	30	27	27
Transport	1426	2519	1897	1529	1667	1754	1503	1097	1025
Biomass burning	3280	2954	2789	2506	2754	3270	2496	2512	2389
Total	8035	7113	7311	5308	5799	6082	5823	4346	4286
<i>IPCC total</i> ^b		15200	17000	9100	15200	16400	19000	7500	17700
OC									
Residential	6246	3165	6054	2599	2702	2422	4801	1957	2082
Industry	1281	639	900	491	621	182	287	92	170
Power	22	28	23	24	23	32	24	20	21
Transport	1330	2306	1709	1335	1518	873	1030	545	697
Biomass burning	25425	22598	21383	19716	21185	24594	18441	19725	18123
Total	34305	28737	30069	24166	26048	28103	24584	22340	21094
<i>IPCC total</i> ^b		99600	111400	59900	99800	107900	124700	49500	116100
BC/OC ratio									
Energy-related	0.54	0.68	0.52	0.63	0.63	0.80	0.54	0.70	0.64
Biomass burning	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.13	0.13
All sources	0.23	0.25	0.24	0.22	0.22	0.22	0.24	0.19	0.20
<i>IPCC all sources</i> ^b		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
<i>SO₂(as S) from IPCC</i> ^c	66800	83700	92100	46700	59200	67500	103000	28000	34800

^aUnits are in Gg.^bFrom IPCC emission projections [IPCC, 2001].^cFrom RIVM [2001].

combustion in eastern Europe, South Asia, East Asia, and parts of Africa, much of which is abated under the B1 scenario. OC emission distributions and changes for open biomass burning are similar to BC. (Note that the scales for OC open biomass burning are different to the others.)

[47] A summary of the global emission reductions by sector is shown in Table 8 and Figure 3. The greatest sectoral changes are (1) a large decline in emissions from the residential sector, because of the gradual replacement of traditional fossil-fuel and biofuel stoves in the developing world by higher-grade fuels (biogas, natural gas, electricity, etc.) and higher-grade technologies (improved cookstoves, etc.); and (2) an increase in emissions from the transport sector in the near term due to greatly increased numbers of vehicles with less-than-optimal emissions performance. The increase in vehicle emissions would be even larger but for the penetration of improved vehicle types and the relatively rapid turnover of vehicles compared to stationary sources. By 2050, transport emissions are projected to be better controlled. Emissions from open biomass burning also decline, according to the IPCC, for several reasons: (1) the burning of crop residues in the field is gradually banned in most parts of the world; (2) the pressure to consume additional forest and savanna for human habitation is relieved by a slowdown in global population; and (3) the pressure to burn forests and savanna for the provision of additional agricultural land is relieved by greater food supplies worldwide. The pressure to restrict crop burning and residential fuel burning also comes from local and household air quality concerns; although we stress again that the emission reductions associated with such restrictions may not be achieved without focus on this issue.

[48] Uncertainties associated with this kind of forecasting are best treated within a scenario context, as discussed at length by Nakicenovic *et al.* [2000]. They assert that:

... (s)cenarios help in the assessment of future developments in complex systems that are either inherently unpredictable, or that have high scientific uncertainties. In all stages of the scenario-building process, uncertainties of different nature are encountered. A large uncertainty surrounds future emissions and the possible evolution of their underlying driving forces, as reflected in a wide range of future emission paths in the literature. The uncertainty is further compounded in going from emissions paths to ... formulating adaptation and mitigation measures and policies. The uncertainties range from inadequate scientific understanding of the problems, data gaps and general lack of data to inherent uncertainties of future events in general. Hence the use of alternative scenarios to describe the range of possible future emissions.

[49] The IPCC scenarios reflect harmonized pathways of development in which such drivers as population, economic activity, structural and technological change, energy demand, and resource availability are coordinated. Thus, by selecting the full range of scenarios, as we have done, one can span the likely range of future emissions.

[50] In our work there are at least two kinds of uncertainties: those associated with the energy projections and those associated with the emission characteristics. Bond *et al.* [2004] developed a detailed analysis of the latter kind for the base-year 1996 inventory. Uncertainties were developed as 95% confidence intervals. For annual global BC emissions, these values are 3.1 to 10.0 Tg (−30% to +120%) about the mean of 4.6 Tg for energy-related combustion and 1.6 to 9.8 Tg (−50% to +200%) about the mean of 3.3 Tg for open biomass burning. For annual global OC emissions,

the values are 5.1 to 17 Tg (−40% to +100%) about the mean of 8.9 Tg for energy-related combustion and 13 to 58 Tg (−50% to +130%) about the mean of 25 Tg for open biomass burning. The asymmetric confidence intervals are a consequence of the lognormal treatment of emissions. The uncertainties are a composite of uncertainties in all the contributing parameters: FC , EF , X , f_{sub} , f_C , and f_{cont} .

[51] Tables 16 and 17 in *Bond et al.* [2004] show that uncertainties in each of these parameters can contribute to the variance in 1996 global emissions, depending on the source type. Naturally, an additional element of uncertainty is added when a parameter is projected into the future. Qualitatively, we would expect that the additional uncertainty associated with f_{sub} , f_C , and f_{cont} is small because the change in technological performance affecting these factors is likely to be quite limited. Uncertainty in EF (and $EFPM$) may be larger, because we have predicted these changes without the backing of analytically derived historical time series trends in pollutant emission rates from the major source types. Uncertainty in FC is related to the formulation of the IPCC energy scenarios, as discussed above. We believe that the greatest additional element of uncertainty in the forecasts is associated with the technology shares, X , and how they change over time. In the 1996 inventory these shares were among the most difficult parameters to quantify, and uncertainty was based on expert judgment. In the more uncertain task of projecting future emissions, there is no rigorous way to quantify these shares. Though uncertainties in X are not quantifiable at this time, and may never be rigorously quantifiable, we hope that further studies of historically observed trends in technology penetration rates in the major economic sectors will be able to reduce these uncertainties. In the meantime, we observe that the scenario approach recommended by *Nakicenovic et al.* [2000] has been the only method used to estimate future emissions of any species. Going beyond this approach will require the efforts of the entire emission forecasting community, and we recommend that such discussions begin.

[52] Table 8 shows the development of BC/OC emission ratios over time. The major trend is an increase in the BC/OC ratio associated with energy-related combustion from about 0.5 at present to 0.5–0.7 in 2030 and 0.5–0.8 in 2050. This suggests an increase in positive radiative forcing (warming) due to carbonaceous aerosols from energy-related combustion. The physical explanation for this trend is simple: inefficient combustors tend to yield emissions with a low BC/OC ratio, and they are also the most likely targets for elimination in the future. The BC/OC ratio from biomass burning stays constant at about 0.13. For all source types, the BC/OC ratio varies only slightly in the range of 0.20–0.25.

[53] In Table 8, we show the values reported by the IPCC for future BC and OC emissions [IPCC, 2001]. The absolute values of these emissions should not concern us too much, because they were derived in a rudimentary way, as discussed earlier. However, it is interesting to examine the relative future changes in emissions assumed by the IPCC for modeling purposes. The method used was to scale base-year BC and OC emissions to changes in anthropogenic CO emissions. While this method may be a reasonable first approximation, it is fundamentally flawed; CO emissions are for the most part uncontrolled and determined solely by the efficiency of combustion,

whereas carbonaceous aerosol emissions are determined only partly by combustion efficiency and partly by particulate control technology, the use and performance of which will change considerably over time. In addition, CO and BC are not always correlated; for example, gasoline engines emit large amounts of CO and little BC, whereas diesel engines are large emitters of BC but not of CO. The IPCC methodology forecasts future trends of increasing carbonaceous aerosol emissions under the A1B, A2, and B2 scenarios, with only B1 showing a decline. Naturally, these trends are similar to the IPCC CO emission trends. In contrast, we project that emissions will decrease under all four scenarios. The BC/OC ratio calculated by the IPCC (0.15) is lower than ours, which may be partly due to the inclusion of secondary organics, and is apparently constant over all time and all scenarios. This is a consequence of the simplicity of the methodology and is inadequate for developing insight into the interplay of black and organic carbon emissions in the future and the net effect on radiative forcing.

[54] As BC and OC emissions change in the future along each of the scenario pathways, SO₂ emissions also change, and hence the potential formation of sulfate aerosol changes. By examining the SO₂ emission changes from the same IPCC forecasts [RIVM, 2001], we can make some observations on the likely net effect of changes in carbonaceous and sulfate aerosols combined. Table 8 shows the SO₂ emissions corresponding to each of the nine scenarios studied. The trends are in accordance with the graphs shown in Figures 5 to 13a–13d of the IPCC emissions report [Nakicenovic et al., 2000]: B1 and B2 show a decrease from the base year, while A2 shows a strong increase and A1B initially increases and then returns to base-year levels by 2050. With BC acting to warm the climate and OC and SO₄ acting to cool the climate, it is important to examine the directional changes of the three species from energy-related sources, which are the ones readily amenable to change by human intervention (i.e., omitting open biomass burning from the discussion). For three of the four scenarios, the sulfate aerosol changes act in the same direction as the carbonaceous aerosol emission changes as regards their radiative forcing. Pathways B1 and B2 are both strongly directed toward increased net warming in the near- and long-term, because the increase in BC/OC ratio is accompanied by a decrease in SO₄. The changes along the A2 pathway are strongly associated with net cooling, as a small decrease in the BC/OC ratio accompanies a large increase in SO₄. The A1B scenario shows no clear directional signal.

[55] It is also instructive to examine the driving forces that lead to these overall global trends in BC and OC emissions in the future. Table 9 and Figure 6 show the components of the emission changes for the 2030A1B scenario, as an illustrative example. In particular, we can examine from these data the competing forces of energy growth and technology improvement. The net effects of energy growth and fuel switching (coal to oil to gas, for example) under the IPCC energy forecasts are to increase emissions. If technology were to remain static at current levels of performance (first row of Table 9), emissions would undoubtedly increase, by as much as 56% for BC.

Table 9. Components of Future Emissions and Mitigation Cases for the 2030A1B Scenario

Cases	BC		OC	
	Tg	Δ	Tg	Δ
Components of future emissions:				
Energy growth (EG) only	12.5	+56 ^a	36.3	+5.7 ^b
EG + improved collection efficiency (CEF)	12.5	+55 ^a	36.3	+5.7 ^b
EG + CEF + changed technology splits (TS)	10.7	+33 ^a	33.5	-2.5 ^b
EG + CEF + TS + improved EFPM = final estimate	7.1	-11 ^a	28.7	-16 ^b
Mitigation cases for 2030:				
1 All residential biofuel eliminated or replaced by biogas	6.4	-11 ^c	26.6	-7.6 ^d
2 All residential biofuel burned in improved stoves	6.6	-7.0 ^c	27.1	-5.9 ^d
3 Modernization of all traditional industries	7.0	-1.2 ^c	28.5	-0.9 ^d
4 All superemitting vehicles replaced	6.2	-13 ^c	27.9	-3.2 ^d
5 Global ban on open burning of crop residues	6.6	-6.9 ^c	26.4	-8.2 ^d
6 Cases 1 + 3 + 4 + 5	5.0	-30 ^c	23.0	-20 ^d

^aChange (%) relative to the 1996 value of 8.0 Tg.

^bChange (%) relative to the 1996 value of 34.3 Tg.

^cChange (%) relative to the 2030 value of 7.1 Tg.

^dChange (%) relative to the 2030 value of 28.7 Tg.

The effect of improvements in particle collection efficiency in such devices as electrostatic precipitators is negligible (second row); this is because such devices are currently highly effective at capturing released particles and because they are applied in the industry and power sectors where the releases from the combustion zones are already low in carbonaceous aerosols. Changed technology splits dampen the increases in emissions (third row), as new users switch from older, less efficient technologies to newer, more efficient technologies to meet the same energy services, and the older technologies are gradually phased out. This component yields a net reduction in OC emissions, but still an increase in BC emissions of 33%. It is only when the improvements in PM emission factors are added (fourth row) that the emission reductions are fully achieved. This analysis suggests that a focus on selected critical technology improvements (in key rows in Table 3) would greatly aid in the reduction of carbonaceous aerosol emissions.

[56] The bottom half of Table 9 shows some mitigation cases, as examples of what additional emission reductions might be able to be obtained by specifically focusing control initiatives on those source types that generate the largest amounts of carbonaceous aerosols. These are reductions above and beyond the reductions obtained by the fuel switching already embodied in the IPCC 2030A1B scenario and the technology improvements incorporated into our model. Five cases are presented: (1) the complete elimination of residential biofuel combustion worldwide and its replacement by biogas or similar fuel with essentially zero BC and OC emissions; (2) all biofuel that is projected to be burned in traditional stoves or in open fires to be burned instead in improved cookstoves; (3) modernization of traditional biofuel industry in developing countries through the use of solid-fuel boilers with emission controls or similar technology; (4) elimination of all superemitting vehicles worldwide and their replacement with well-controlled vehicles; and (5) a global ban on the open burning of crop residues in fields.

[57] Option 4 yields the greatest additional reduction in BC emissions (13%). Option 5 yields the greatest additional reduction in OC emissions (8%). If all these options

could be introduced simultaneously (except option 2 which is superseded by option 1), additional reductions of about 30% in BC emissions and 20% in OC emissions might be possible. These values are not very dependent on scenario. They represent about the best that could be done

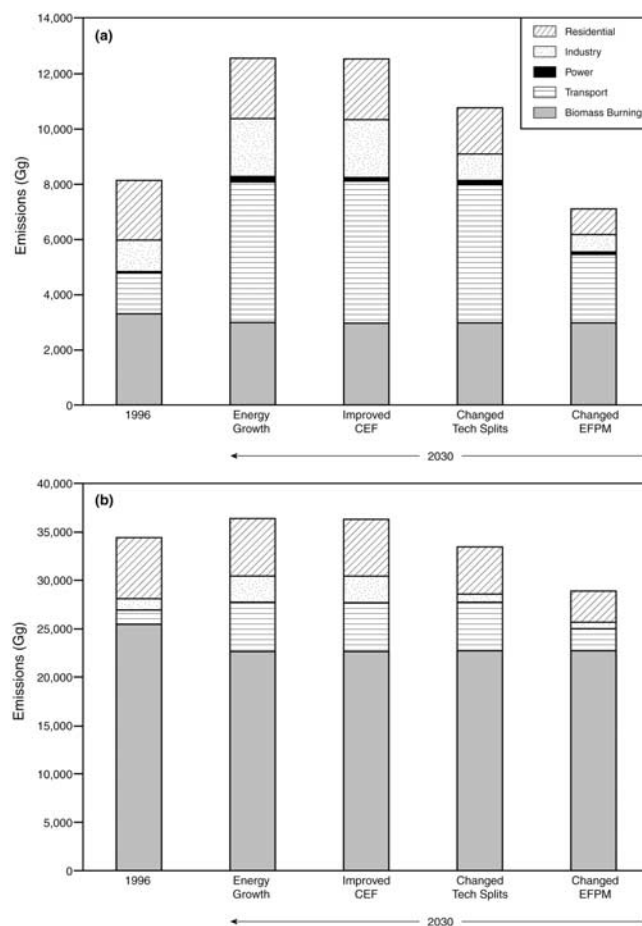


Figure 6. Components of emission changes (cumulative) between 1996 and 2030 under the A1B scenario [CEF = particulate control efficiency]: (a) BC; (b) OC.

to limit future carbonaceous aerosol emissions by additional measures.

6. Conclusions

[58] This paper is the first detailed attempt to forecast future emissions of primary carbonaceous aerosols. It takes a recent global inventory for the year 1996 and projects it to the years 2030 and 2050 using four scenarios of IPCC growth rates for fuel use by sector and world region, the embedded IPCC forecasts of changing global patterns of fuel use, our own projections of evolving combustion technology and particulate control technology, and our own forecasts of improved technology performance. Our major conclusion is that we expect a decline in emissions of both BC and OC over time under all scenarios, as improved technology and changed patterns of fuel use lead the world away from the traditional source types and solid fuels that contribute most heavily to carbonaceous aerosol emissions today. These reductions are achieved in the face of growing energy use and increased fossil-fuel combustion worldwide.

[59] Specifically, we project that global BC emissions will decline by 9–34% by 2030 and by 24–47% by 2050, depending on the scenario. We project that OC emissions will decline by 12–30% by 2030 and by 18–39% by 2050. These reductions represent composites of trends in energy-related combustion and open biomass burning, and reflect a full range of trends in the underlying driving forces. These results are contrary to some of the simplistic projections of BC/OC emissions made by the IPCC, which suggest increasing emissions under three of the four IPCC scenarios. We estimate that there are additional reductions possible (up to 30% for BC and 20% for OC) if some other, more drastic measures could be implemented that we do not expect to see happen in the normal course of events.

[60] Not all the news is good. In some parts of the world, particularly South America, northern Africa, the Middle East, South Asia, Southeast Asia, and Oceania, we project increasing BC emissions under several of the scenarios. OC emissions are generally stable or declining in all scenarios. Particularly difficult to control are BC emissions from the transport sector, which are projected to increase under most scenarios. We also expect that the global BC/OC emission ratio for energy sources will increase in the future; this signifies that the trends in carbonaceous aerosol emissions will probably shift toward increased net warming of the climate system. The accompanying changes in sulfate aerosol will tend to reinforce the carbonaceous aerosol trends.

[61] Not all concerns about our understanding of current emissions of carbonaceous aerosols have been removed at the present time. Inconsistencies are still found between modeled aerosol concentrations and optical properties that use current inventories and field measurements of the same quantities, especially in China and India. These may or may not be related to the reliability of current emission estimates; only additional research will tell. However, to the extent that they are associated with emissions problems, such factors as missing sources and incorrect emission factors may still exist in the 1996 inventory and be carried over to the future years projected in this study. Note that Bond *et al.* [2004] address uncertainty in the 1996 inventory. Energy projec-

tions are inherently uncertain and are treated through scenario analysis, as discussed by the IPCC [Nakicenovic *et al.*, 2000].

[62] Although our modeling of emitting sources in the future is based on reasonable assumptions and a formal methodology, we acknowledge that our treatment of future emission factors and technology splits is rather simplistic, in the sense that we have not developed marginal performance or abatement curves for each technology option nor calibrated the assumptions against actual, historical technology diffusion rates. In future work, we intend to formalize and test these assumptions where such supporting evidence can be found. At the conclusion of that work, we should have a more complete view of likely future emissions of carbonaceous aerosols that will have important implications for possible global and regional climate modification in the rest of this century.

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