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Dissecting future aerosol emissions: warming tendencies and mitigation opportunities

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Abstract Future global emissions of aerosols will play an important role in governing the nature and magnitude of future anthropogenic climate change. We present in this paper a number of future scenarios of emissions of black carbon (BC) and organic carbon (OC) by world region, which we combine with sulfate (SO_4) assessed in terms of the emissions of its precursor, SO_2. We find that aerosol emissions from the household and industrial sectors are likely to decline along almost all future pathways. Transportation emissions, however, are subject to complex interacting forces that can lead to either increases or decreases. Biomass burning declines in many scenarios, but the Amazon rainforests remain vulnerable if unsustainable economic growth persists. East Asia is the key region for primary aerosols, and trends in China will have a major bearing on the direction and magnitude of releases of BC (expected reductions in the range of 640–1290 Gg), OC (reductions of 520–1900 Gg), and SO_2 (ranging from an increase of 21 Tg to a reduction of 30 Tg). Analysis of joint BC, OC, and SO_2 emission changes identifies a number of key world regions and economic sectors that could be effectively targeted for aerosol reductions.

1 Introduction

The importance of tropospheric aerosols in modifying global climate regimes has been known for many years. Initial work on man-made aerosols focused on sulfate (SO_4), because it was best known and could be linked to emissions of SO_2, which were also relatively

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well known (Wigley 1991; Lelieveld and Heintzenberg 1992; Charlson et al. 1992; Kiehl and Briegleb 1993). In the past five years, the importance of carbonaceous aerosols for 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 2000, 2001, 2002; Chameides and Bergin 2002; Chung and Seinfeld 2002, 2005). Black carbon (BC) has been proposed as possibly the second most important warming species after CO_2 (Hansen et al. 2000; Jacobson 2000, 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). Recent modeling may have restored methane as the second most important greenhouse species (Hansen et al. 2005), and there is increasing interest in the roles of ozone and nitrates, but BC still maintains a high profile in global climate research. Organic carbon (OC) is not so well understood at present but just as important and the subject of ongoing research (Jacobson et al. 2000; Claeys et al. 2004; Kalberer et al. 2004; Maria et al. 2004); note that this present paper addresses only primary emitted OC, not secondary OC formed in the atmosphere. Finally, the ability of carbonaceous aerosols to modify local climatology in regions where emissions are high, like China and India, has been postulated (Ackerman et al. 2000; Ramanathan et al. 2001a,b; Lelieveld et al. 2001; Menon et al. 2002).

Despite the acknowledged importance of aerosols to climate change, our understanding of the source types, source strengths, and global distribution of aerosols is still rather rudimentary. In particular, we do not have a good understanding of what the future holds for global aerosols. The Intergovernmental Panel on Climate Change (IPCC) and many individual researchers have studied the future of gaseous emissions out as far as 2100 (see IPCC 2001), but similar investigations are seriously lacking for particles. However, with the recent release of carbonaceous aerosol emission forecasts to 2050 under a number of IPCC scenarios (Streets et al. 2004), based on a new and detailed current inventory of carbonaceous aerosol emissions (Bond et al. 2004), we are now better placed to try to understand what potential pathways of aerosol emissions face us in the future.

The purpose of this paper is to combine the new forecasts of Streets et al. (2004) with the SO_2 forecasts of the IPCC along a variety of future pathways (Nakicenovic et al. 2000; Grubler 1998) in order to develop a uniform and consistent set of projections of emissions of the three major man-made atmospheric aerosols: black carbon (BC), organic carbon (OC), and sulfate (SO_4)–using SO_2 emissions as a proxy. Because BC has a warming effect and OC and SO_4 both have cooling effects, it is not at all clear what the net effect of future emission changes will be; for the first time we give some insight into this question. We also dissect the full array of future emission projections to provide observations about the regional and sectoral trends in these species, highlighting worrisome negative outcomes to combat and positive mitigation opportunities to exploit.

2 Data and method

This work is based on a data set of future emissions of BC and OC for the years 2030 and 2050 (Streets et al. 2004). That method extrapolated the 1996 inventory of Bond et al. (2004) using IPCC scenarios (Nakicenovic et al. 2000; IPCC 2001), as formulated by the IMAGE group at world-region level (RIVM 2001). The base-year inventory (Bond et al. 2004) builds on previous work to characterize aerosol emissions (Streets et al. 2001, 2003a,b) and uses 1996 IEA energy data (IEA 1998a,b) for its development of world fuel use by region and sector. The new representation of present-day carbonaceous aerosols by Bond et al. (2004) is an update and improvement on previous inventories by Cooke and Wilson (1996) and Cooke et al. (1999).

The individual BC and OC calculations of aerosol emissions for 1996, 2030, and 2050 in Streets et al. (2004) were performed for 112 combinations of sector, fuel, and technology, which are consolidated for this work into six sectoral groupings: household, industry, power generation, transportation, biomass burning, and total. A similar set of SO_2 emissions for 1996, 2030, and 2050 were extracted directly from the IMAGE formulations of the IPCC scenarios and are therefore consistent with the BC and OC calculations with regard to fundamental assumptions about future energy, economic, and social driving forces.

Figure 1 schematically illustrates the data flows in the calculations of BC and OC emissions and their relationship with SO_2 emissions. The IMAGE formulations of the IPCC scenarios provide SO_2 emissions directly, together with the characteristics of energy and economic growth needed to forecast BC and OC emissions in the future. Base-year estimates of BC and OC emissions for 1996 are calculated from detailed IEA energy statistics (IEA 1998a,b) coupled with technology splits and emission factors for 1996 (Bond et al. 2004). We use region- and scenario-specific IPCC energy growth data to develop the future fuel-use patterns, and we use region- and scenario-specific IPCC economic growth data to develop the future technology splits and emission factors, as described in Streets et al. (2004). Base-year and future emissions of BC and OC are then brought together with the

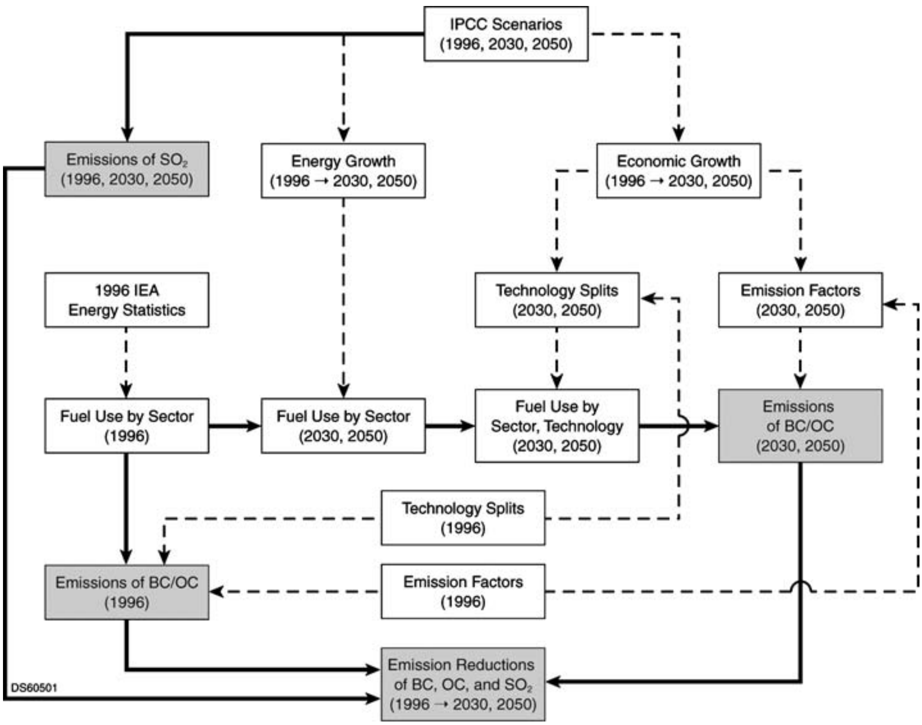

Fig. 1 Methodology for developing estimates of future emission reductions of BC, OC, and SO_2.

SO_2 emissions, and emission reductions from 1996 to 2030 and from 1996 to 2050 are calculated.

We examine emission changes for four IPCC scenarios–A1B, A2, B1, and B2–the descriptions of which are provided in Table 1. These four scenarios span the likely range of future emissions pathways; and Table 1 shows their attributes of population, *per capita* GDP, and coal use, which are key determinants of aerosol emissions. Emission trajectories are calculated for 17 world regions–Canada, U.S.A., Central America, South America, North Africa, West Africa, East Africa, South Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, Southeast Asia, Oceania, and Japan–the boundaries of which can be found in IMAGE documentation (RIVM 2001).

Figure 2 provides some examples of the absolute values of BC, OC, and SO_2 emissions in 1996, 2030, and 2050 for four selected regions across the full range of scenarios. BC and OC emissions are generally expected to decrease in the future, the major exception being the possibility of increased OC emissions in South America due to increased vegetation burning in the Amazon. SO_2 emissions are generally stable or declining in the developed world, but increases are possible in developing regions as a result of high economic growth coupled with poor environmental control. Generally, the range of possible future outcomes is much larger for developing and newly industrializing regions than it is for developed regions like the U.S.

There are two major uncertainties in these emission projections: those associated with the emission characteristics and those associated with the energy forecasts. Bond et al. (2004) developed a detailed analysis of the former for the 1996 BC and OC emissions. Uncertainty ranges were developed as 95% confidence intervals, based on literature measurements of emission factors. For global BC emissions, these ranges are -30% to $+120\%$ for energy-related combustion and -50% to $+200\%$ for open biomass burning. For global OC emissions, the values are -40% to $+100\%$ for energy-related combustion and -50% to $+130\%$ for open biomass burning. The asymmetric confidence intervals are a consequence of the lognormal treatment of emissions. These uncertainty estimates will be higher for future years, because we make assumptions about technology improvements out to 2030 and 2050 that affect emission factors, but the additional uncertainty is unquantifiable. Parallel uncertainty estimates for present-day SO_2 emissions have only been made for Asian countries (Streets et al. 2003a). Uncertainty estimates range from $\pm$ 9% for Japan to $\pm$35% for India. Uncertainties are lower for SO_2 than for BC and OC, because emissions are constrained by the sulfur content of the fuels. We have extended the Asian approach to global SO_2 emission estimates and calculate a 95% confidence interval of $\pm$14%. As regards the uncertainty of the energy forecasts, it is not possible to put quantitative uncertainty bounds on future energy use, and we agree with Nakicenovic et al. (2000) on behalf of the IPCC that the multiple scenario approach is the most effective and well-grounded way to accommodate the uncertainty of the future. It is for this reason that we analyze four future scenarios with no expressed preference for any of them.

3 Results

In this work we concern ourselves with the emission outcomes in each of 17 world regions, expressed as emission reductions between 1996 and 2030 and between 1996 and 2050. A positive value of emission reduction means that the future emission value is less than the 1996 value. The regional results for each scenario/year combination are the endpoints shown in Figs. 3–10 (17 world regions $\times$ 4 scenarios $\times$ 2 years $=$ 136 maximum

Table 1 Key global attributes of selected IPCC scenarios (Sources: IPCC 2001; Nakicenovic et al. 2000; RIVM 2001)

		1996			2030			2050		
Scenario	Scenario description	Pop. (10^6)	GDP ($ US/cap)	Coal use (EJ)	Pop. (10^6)	GDP ($ US/cap)	Coal use (EJ)	Pop. (10^6)	GDP ($ US/cap)	Coal use (EJ)
A1B	The A1 scenario describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. The designation "B" indicates a balance among fossil-fuel and other technologies.	5,789	5,017	93.2	8,190	12,277	185.3	8,716	24,239	234.1
A2	The A2 scenario describes 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.	5,799	5,007	93.2	9,254	6,959	167.9	11,309	8,564	255.2
B1	The B1 scenario describes a convergent world with low population growth but rapid changes in economic structure toward a service and information economy. There are reductions in material intensity and the introduction of clean and resource-efficient technologies.	5,789	5,017	93.3	8,190	10,600	110.0	8,716	18,361	118.8
B2	The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid technological change.	5,784	5,021	93.2	8,384	9,393	144.7	9,386	13,637	124.2

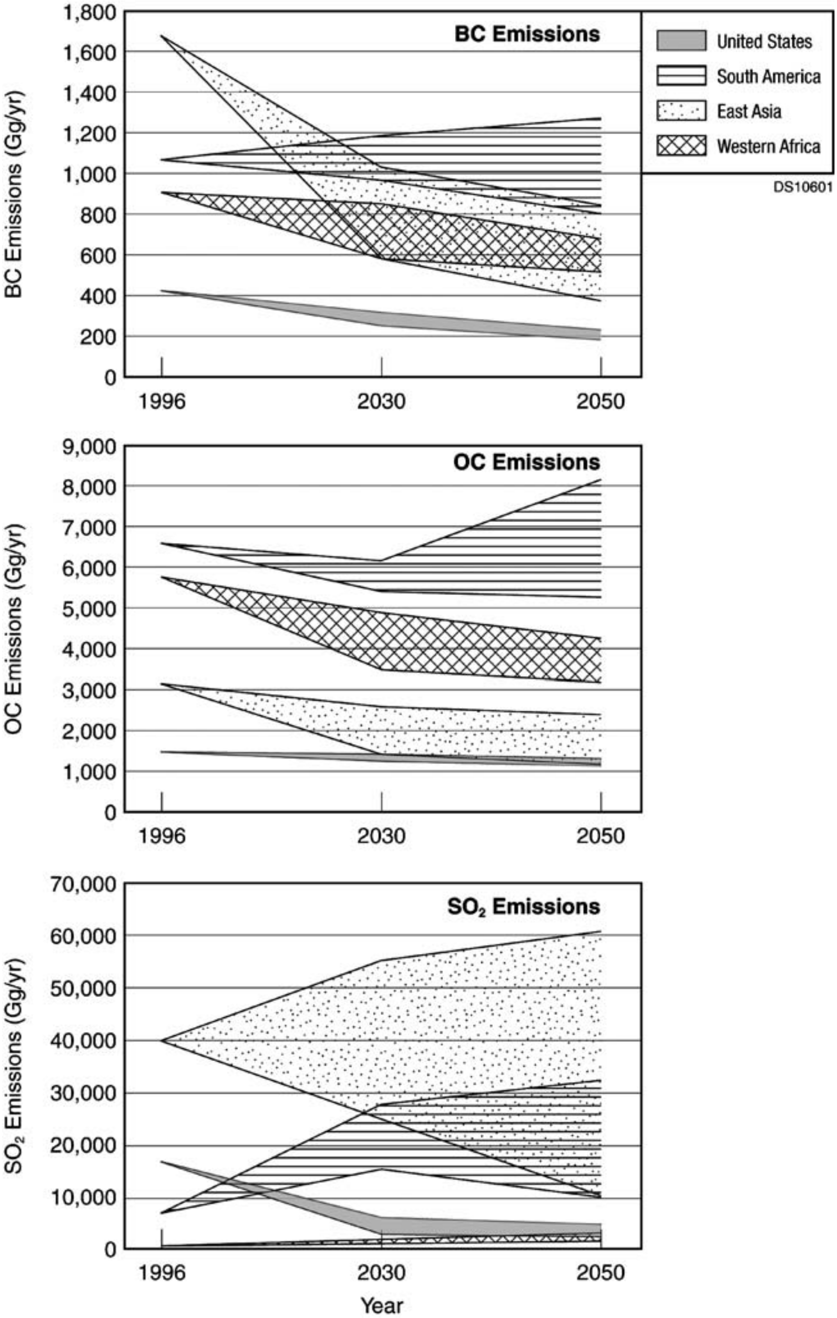

Fig. 2 Ranges of emission forecasts across all four IPCC scenarios for BC, OC, and SO_2 emissions in four selected world regions.

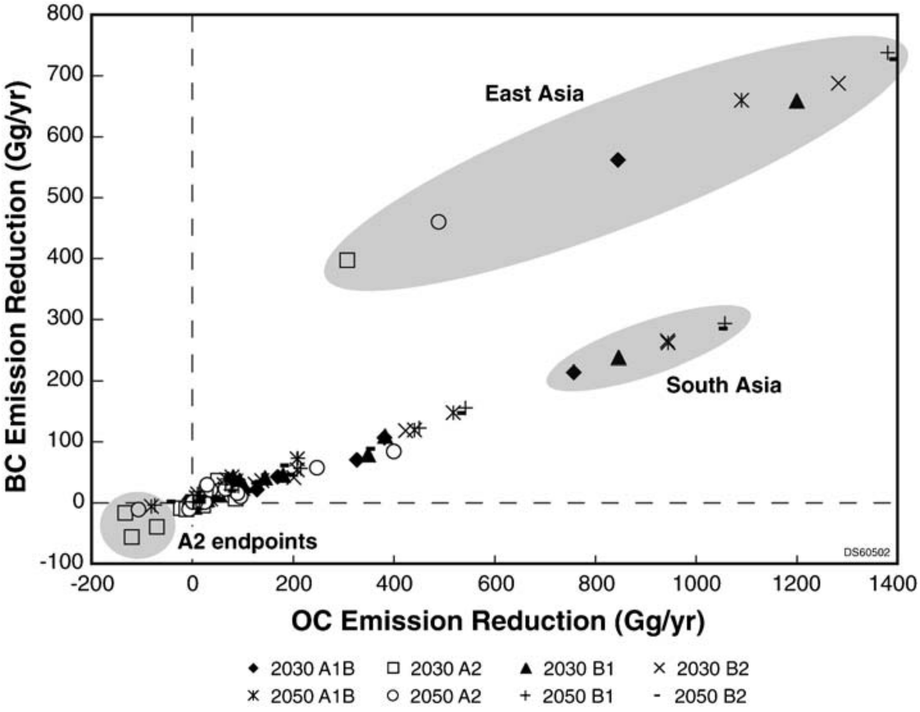

Fig. 3 Regional BC and OC emission reductions in the household sector

possible endpoints). These endpoints are examined for various sectors and combinations of BC, OC, and SO_2. We review the forecasts of BC and OC emissions by sector, showing important features of the expected trends for each scenario, year, and world region. Table 2 summarizes the results of this inter-sectoral comparison, drawing out nine key components that have essentially uniform characteristics. We specifically examine four sectors: household, industry, transportation, and biomass burning. Primary carbonaceous emissions from power generation are too small to be worthy of separate study (Bond et al. 2004). We often present BC/OC ratios because both species are emitted during combustion but in different proportions depending on the fuel type and sector; because BC induces warming and OC induces cooling, a high BC/OC ratio can be considered indicative of a greater tendency towards warming than a low BC/OC ratio. Of course, the actual net radiative effect of a given change in emissions can only be developed with a regional climate model.

3.1 Household sector

The largest reductions of BC and OC emissions are found in the household sector (Fig. 3). A linear relationship ($R^2 = 0.98$) is obtained for the combination of all world regions except East Asia (because of the use of coal, see below); the linearity is a reflection of the replacement of biofuel combustion (in stoves, cookers, and heaters) with clean fuels. Whether the biofuel is wood or agricultural waste and whether the clean fuel is biogas, LPG, or electricity, there are few differences in the changes in primary carbonaceous aerosol

Table 2 Summary of sectoral, regional, and scenario analysis of BC and OC emission reductions between 1996, 2030 and 2050

Sector/world regions	Ranges of regional emission reductions achieved (Gg)		No. of points[a]	Slope (BC/OC ratio)	Intercept	R^2
	BC	OC				
Household (all except East Asia)	−60 to +290	−130 to +1060	128	0.27	2.2	0.98
Household (East Asia only)	+400 to +740	+310 to +1390	8	0.31	310	0.99
Industrial (developing world, except East Asia)	−20 to +70	0 to +210	64	0.26	−3.6	0.63
Industrial (East Asia only)	+300 to +480	+210 to +330	8	1.6	−37	0.92
Industrial (developed world)	0 to +70	0 to +30	64	2.1	−3.2	0.93
Transport (all except U.S., OECD Europe, Japan)	−230 to +50	−220 to +160	112	0.51	−33	0.40
Transport (OECD Europe and Japan only)	0 to +190	0 to +80	16	2.3	−2.4	1.00
Transport (U.S. only)	0 to +170	0 to +110	8	1.6	−16	1.00
Biomass burning (all)	−250 to +480	−2030 to +3490	136	0.14	−4.9	0.99

[a]This column indicates the number of emission endpoints corresponding to each selected sector/world region combination. The maximum number of endpoints is 136 (17 world regions × 4 scenarios × 2 years). For one sector/region combination there are 8 endpoints (4 scenarios × 2 years).

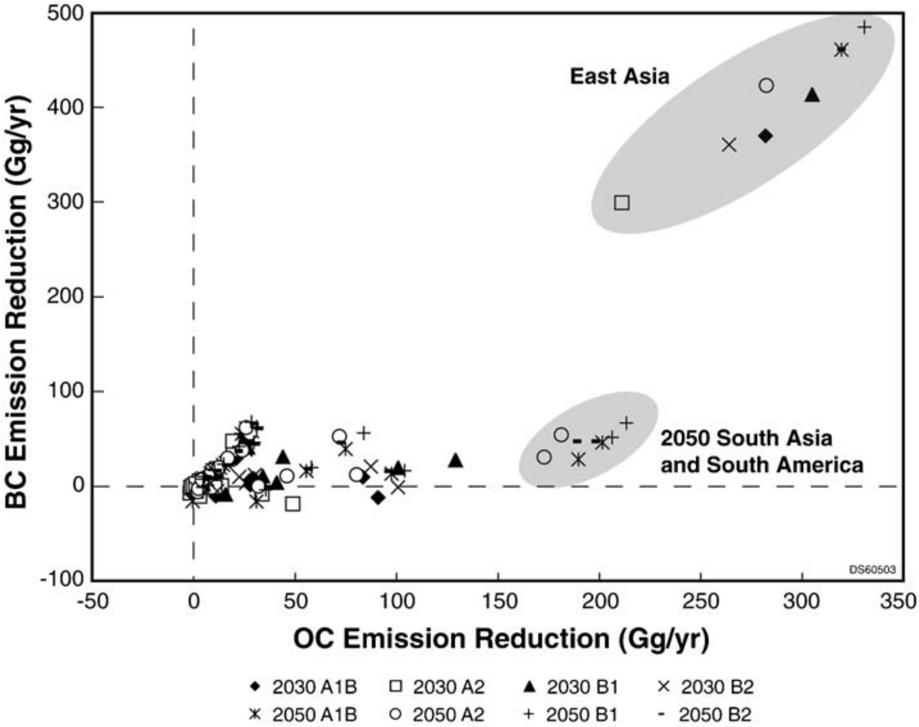

Fig. 4 Regional BC and OC emission reductions in the industrial sector

emission rates. This is because the biofuels have similar BC and OC emission rates, within uncertainty limits (Andreae and Merlet 2001), and the emission rates for the clean substitutes are essentially zero. The BC/OC ratio for these reductions is 0.27 (see Table 2). Emission reductions for both BC and OC are expected for almost all endpoints, of which the greatest opportunities are the replacement of biofuel use in South Asia (210–290 Gg BC, 760–1060 Gg OC). (Ranges presented in this paper for emission reductions reflect the highest and lowest values of the differences between future and 1996 emissions among all scenarios.)

For near-term (2030) endpoints under the A2 scenario, however, small increases in BC (< 100 Gg) and OC (< 200 Gg) emissions are projected, mostly in African regions. The A2 scenario reflects high population growth coupled with low economic growth and slow technology turnover. The keys to averting these aerosol emission increases in the household sector in Africa are clearly rapid economic development and poverty reduction to reduce rural biofuel combustion. The greatest reductions and the widest *range* of reductions are forecast for East Asia (predominantly China): 400–740 Gg BC and 310–1390 Gg OC. Because coal still plays a major role in the household sector in China, relatively greater reduction in BC than OC is achieved, with a BC/OC ratio of 0.31. We conclude that the household sector should be a prime target for reductions in carbonaceous aerosol emissions, particularly China's household sector, which we have commented on in more detail elsewhere (Streets et al. 2001; Streets and Aunan 2005). Overall, the outlook seems bright for reduced worldwide emissions from the household sector in the future.

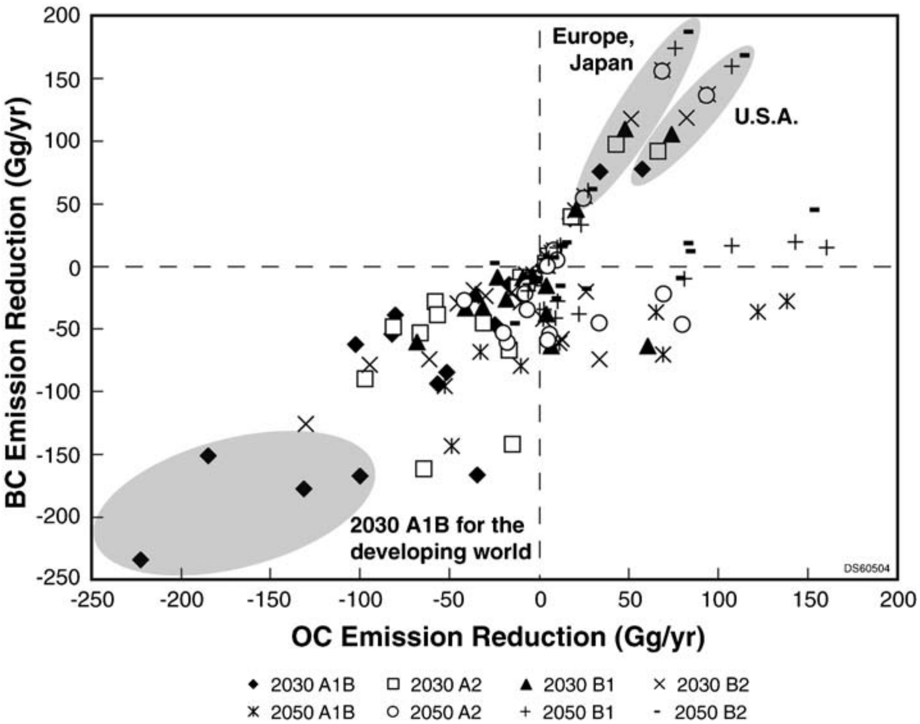

Fig. 5 Regional BC and OC emission reductions in the transportation sector

3.2 Industrial sector

The industrial sector also reflects a consistent pattern of reductions in both BC and OC emissions in the future, even under the A2 Scenario (Fig. 4). We attribute this to a spreading awareness of the polluting nature of poorly controlled industrial plants: their primary carbonaceous aerosol emissions are easily visible as black or gray smoke rising from prominent smokestacks. Regulations controlling industrial particulate emissions are already in place in most parts of the world, and they are continually being tightened under community, regional, or national pressures. Technological innovation is an important driving force for future industrial aerosol emissions. Our model considers the time development of 35 separate industrial emitter types, and further details of the modeling approach can be found in Streets et al. (2004). Because of steps already taken, the additional regional reduction opportunities for BC emissions are small (<70 Gg), except in East Asia. Reductions available in OC emissions are higher (up to 220 Gg), especially in South Asia and South America.

We find three distinct segments of industrial carbonaceous aerosol emission reductions. In the developed world, further reductions are uniform ($R^2 = 0.93$) but limited (see Table 2); and the BC/OC ratio of the reductions is high (2.1), signifying a relative tendency toward climate cooling. In the developing world, the situation is more diverse, indicative of a wider array of industrial technology types, levels of technology development, and types of fuel used ($R^2 = 0.63$). As indicated above, regional OC reduction opportunities are larger in the developing world (as much as 210 Gg in South Asia and South America), but the BC/OC ratio

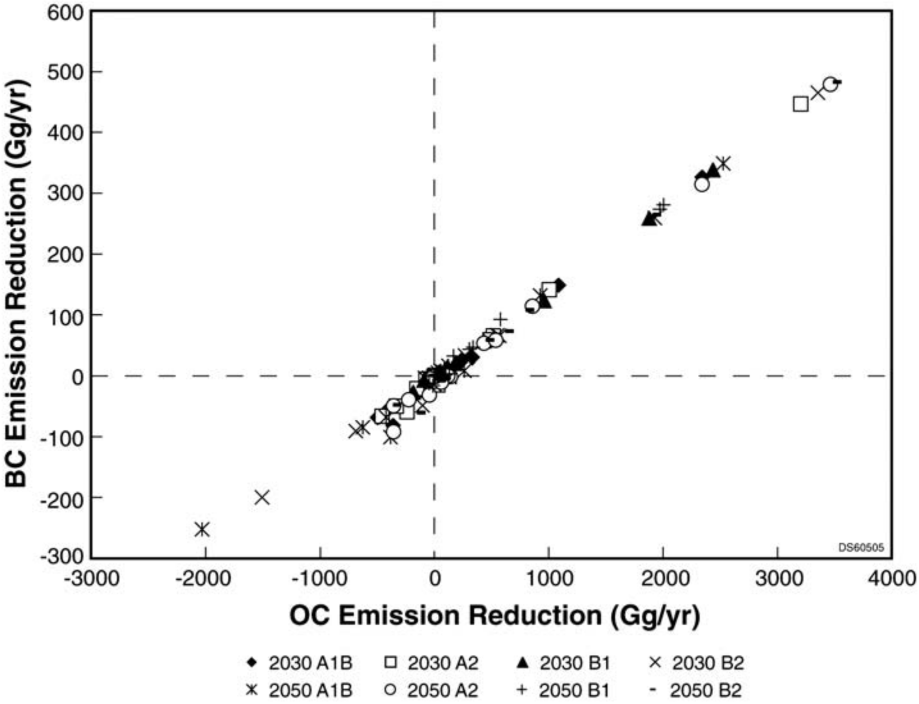

Fig. 6 Regional BC and OC emission reductions from biomass burning changes

of the reductions is much lower, at 0.26. For the third key component of industrial emissions, East Asia, opportunities are large (300–480 Gg BC, 210–330 Gg OC), and the BC reduction potential is greater because of the predominance of poorly controlled, coal-fired industrial facilities in China (BC/OC reduction ratio of 1.6).

3.3 Transportation sector

The situation for emissions from the transportation sector is more complex. Reductions are projected for some regions, increases for others. For the developed world, continuing emission reductions are expected, as vehicle emission standards for fine PM continue to be tightened, for example, with the addition of particle traps. Figure 5 reveals two distinct linear trends of reductions for OECD Europe/Japan (BC/OC = 2.3) and the U.S. (BC/OC = 1.6). Outside these two regions, the situation is much more chaotic ($R^2 = 0.40$): many regions show reductions in OC of up to 160 Gg, while other regions have increasing OC emissions (up to 100 Gg). The direction of the trend in a given region is reflective of the net result of the tension between growing vehicle usage and improving tailpipe emission rates. Most worrying are the results for developing countries under the near-term (2030) A1B scenario, where large aerosol emission increases are projected for the transportation sector (BC up to 230 Gg and OC up to 220 Gg). Along this pathway, vehicle ownership grows very rapidly in concert with rapid economic growth in the developing world. Environmental protection is given less attention in A1B, so the penetration of tight vehicular emission standards is slow.

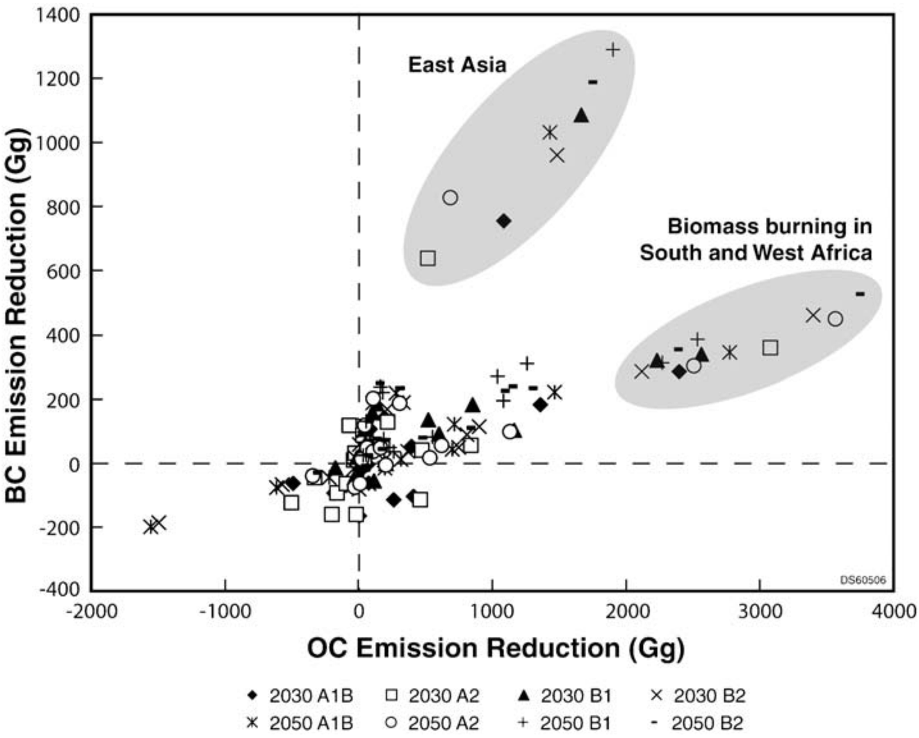

Fig. 7 Regional BC and OC emission reductions from all sectors combined

3.4 Biomass burning

Finally, results for biomass burning are shown in Fig. 6. A very tight correlation is observed for all world regions ($R^2 = 0.99$), reflecting the small differences in emission factors among the types of burning included in this analysis (Andreae and Merlet 2001). Generally, emissions are reduced over time due to the combined effects of fewer requirements to clear forested land for habitation and food, increasing urbanization, and a spreading awareness of the adverse inhalation health effects of burning vegetation outdoors (see Streets et al. 2003b, for a discussion of how these items are treated in the IPCC scenarios). Economic development in South and West Africa is particularly effective in reducing open biomass burning and the resulting aerosol emissions, especially of OC.

The one region of concern is South America, where high population growth, high economic growth, and limited environmental protection under some scenarios lead to further destruction of the Amazon rainforest and consequent aerosol emission increases. OC emissions in South America increase by as much as 2030 Gg under the worst-case scenario. Vegetation burning has the lowest BC/OC ratio of all (0.14), consistent with emission factor measurements (see Andreae and Merlet 2001) that show enhanced OC production compared to fossil-fuel combustion.

3.5 All sectors

We can summarize the sectoral analysis of the nine key components by identifying the top three targets for (a) reducing emissions of BC [East Asia household sector, East Asia

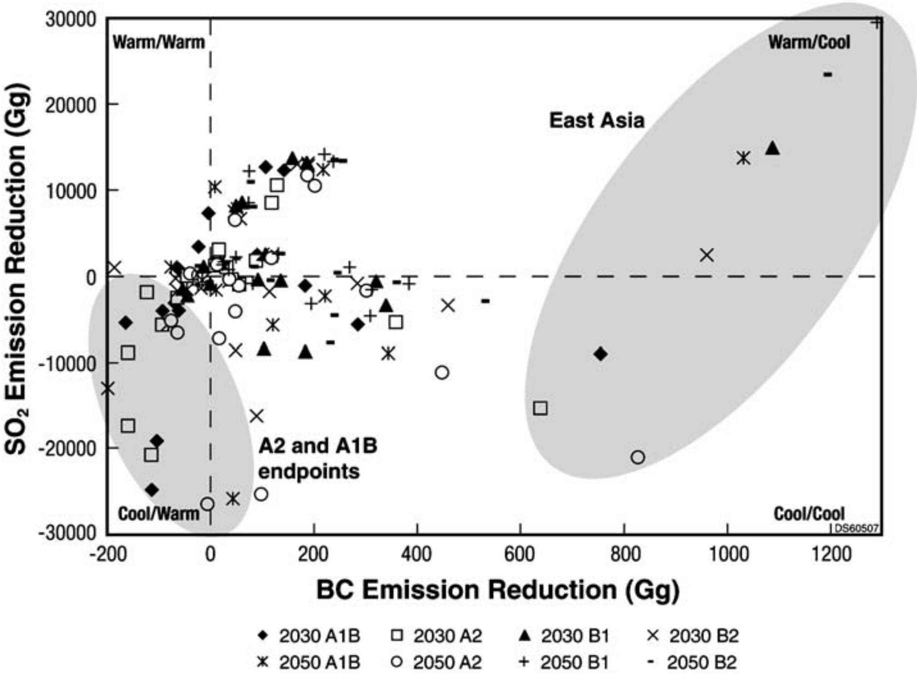

Fig. 8 Regional SO_2 and BC emission reductions from all sectors combined

industrial sector, and biomass burning]; (b) reducing emissions of OC [biomass burning, East Asia household sector, and household sectors in other developing countries]; and (c) maximizing the ratio of BC/OC emission reductions to alleviate global warming [household sector outside East Asia, East Asia household sector, transport sector in OECD Europe/Japan].

Figure 7 shows the BC and OC emission reduction relationship across all sectors combined (total emissions, 136 endpoints). Two prominent components are clear: East Asia, where significant emission reductions (640–1290 Gg BC, 520–1390 Gg OC) are achievable that favor BC; and South and West Africa, where reduced biomass burning leads to significant reductions (260–480 Gg BC, 2120–3490 Gg OC) that favor OC. For the remaining cases, emission reduction endpoints are clustered around the origin, mostly positive but a few negative.

3.6 Sulfate

Adding sulfate to the mix is difficult, because SO_4 is a secondary species formed by oxidation of SO_2 in the atmosphere. Primary SO_4 emissions are small and of little consequence. We indicate in this section the combined effects of changes in primary emissions of BC and OC, coupled with changes in primary emissions of SO_2 as a proxy for changes in secondary SO_4 in the atmosphere. Figure 8 shows the relationship between BC and SO_2 emission reductions. In this figure and the two that follow, we show the warming or cooling tendencies (W or C) of these emission changes in each quadrant. These tendencies are simply determined by the sign of the emissions change of a particular species, i.e., increasing BC emissions implies

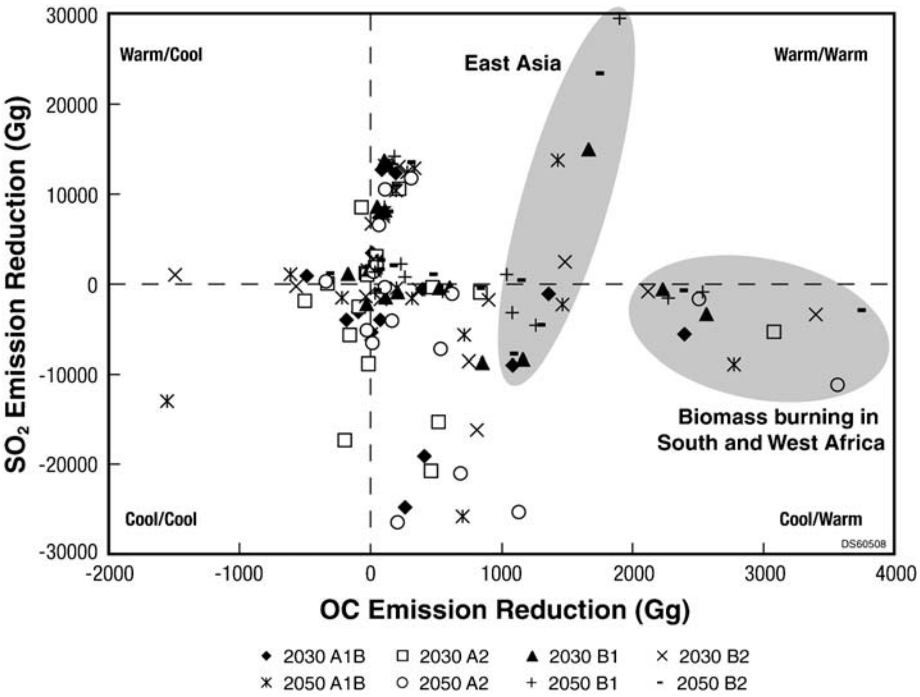

Fig. 9 Regional SO_2 and OC emission reductions from all sectors combined

a warming tendency. When a quadrant indicates a warming tendency for one species and a cooling tendency for the other, we clearly cannot determine the net effect without performing detailed climate modeling. In Fig. 8, many points lie in the W/C or C/C quadrants (SO_4/BC order). Significantly, there are very few W/W endpoints, i.e., few scenarios show BC and SO_4 reinforcing each other in warming the atmosphere. Notable features are a number of C/W points corresponding to both A2 and A1B pathways in developing countries. Here, SO_2 emissions are increasing by significant amounts, in combination with increasing BC emissions, either through population increase and stagnation of technology transfer (A2) or rapid fossil-fueled economic growth (A1B). The major feature, though, is the swath of endpoints for East Asia that span a wide range of SO_2 increases and decreases, all with decreases in BC (W/C and C/C). What happens in China is therefore of high priority. Figure 9 shows in similar fashion the relationship between OC and SO_2. Here, endpoints are more scattered with no clear signal. East Asia shows a similar pattern to BC/SO_2, mostly in the W/W quadrant. Reductions in biomass burning in South and West Africa are positive for OC reduction and slightly negative for SO_2.

Finally, in Fig. 10 we combine all three aerosol species by plotting SO_2 emission reductions against the BC/OC reduction ratio. The latter term is defined, for the year 2030, as: $[BC_{1996}/OC_{1996}] - [BC_{2030}/OC_{2030}]$. Thus, if the BC/OC ratio remains unchanged between the two years, a value of zero is returned. If the BC/OC ratio is reduced over time, a positive value is returned, signifying a cooling tendency. In Fig. 10, a remarkable number of points are clustered around the origin, but five distinct groupings emerge. First, there is a set of W/C (SO_4, BC/OC ordering) endpoints associated with strong BC/OC ratio reductions and mildly positive SO_2 reductions. On the opposite side of the domain are changes in the Middle East

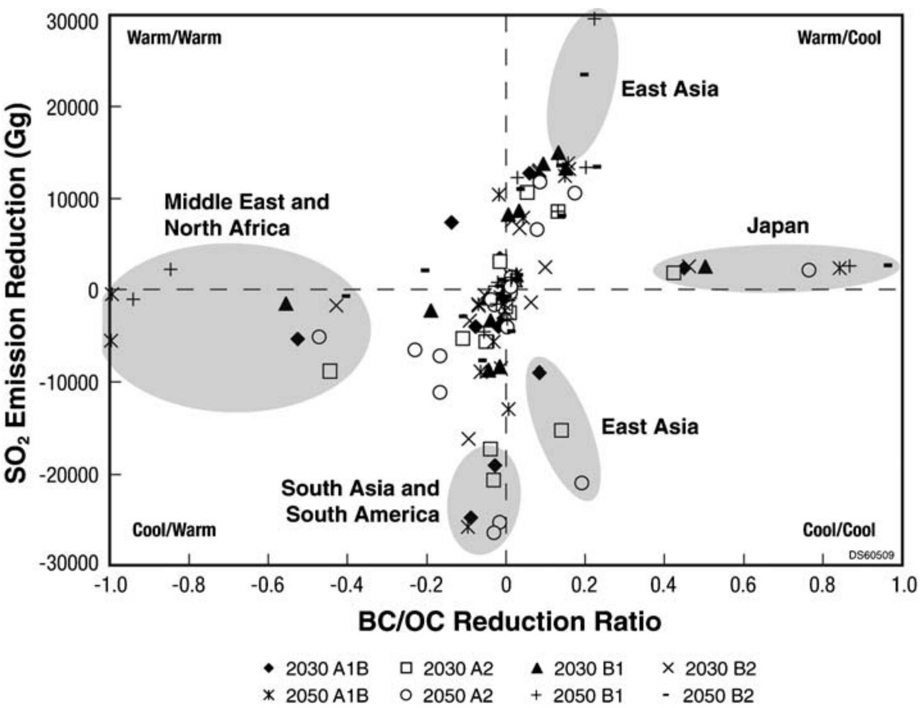

Fig. 10 Relationship between regional SO_2 emission reductions and reductions in the BC/OC emission ratio for all sectors combined

and North Africa that have strong BC/OC ratio increases and mildly negative SO_2 trends (emission increases) (C/W). South Asia and South America are associated with a small increase in the BC/OC ratio and a large increase in SO_2 emissions (C/W). Finally, two sets of points reveal the "swing" region of East Asia, in which small reductions in the BC/OC ratio are associated with either large increases or decreases in SO_2 emissions, depending on the success of environmental control measures to arrest pollution from coal use.

4 Conclusions

This paper presents an overview of future global emissions of the three major radiatively active aerosol species in the atmosphere caused by human activities: BC, OC, and SO_4 (as SO_2). The paper compares and contrasts the contributions of different world regions and emitting sectors. The underlying reasons for the remarkable variations in emission distributions can be understood partly by reference to the patterns of fuel use and human activity around the world, but also by the use of technologies that have widely varying emission rates. As we survey the levels of economic development around the world, we see an array of technologies for delivering a given energy service, ranging, for example, from the primitive (open fires used for cooking) to the sophisticated (cooking on electric stoves powered by nuclear energy).

In order to understand the current patterns of emissions and to be able to predict future emissions and design effective control measures, we need to be able to characterize technologies and fuels around the world in a rather detailed manner. It is not sufficient to simply target particular forms of energy use or particular economic sectors for control, because the emissions of each species are themselves tightly linked and human and economic activities are entwined with environmental progress in complex ways. Substitution of one form of energy use by another in a particular part of the world can fundamentally alter the mix of species emitted to the atmosphere. Any action that we take will influence emissions of all three aerosol species in ways that are not easy to predict – as well as gaseous species, of course. Wigley (1991) stated that it was conceivable that over the next 10–30 years the increased radiative forcing due to SO_2 (and therefore SO_4) concentration changes could more than offset reductions in radiative forcing due to reduced CO_2 emissions. We need to be able to understand the inter-relationships between emissions of aerosol emissions from the perspectives of both future global developments and specific mitigation actions that can be taken.

The first conclusion we reach is that future developments in China, and to a lesser extent South Asia and South America, will significantly influence the magnitude and mix of global aerosol releases in the future. Modernization of the household sector in China will greatly improve the situation, as will improved emission controls and fuel substitution in the industrial sector. Emissions from the household sector in Africa will increase if population grows rapidly, economic development is slow, and technology transfer stagnates (A2 Scenario). Generally speaking, though, the outlook is promising for both the household sector and the industrial sector. The most worrisome sector is transportation. While continued tightening of vehicle emission standards in the developed world will reduce primary aerosol emissions, increases are likely in many parts of the developing world, especially where environmental protection does not keep pace with rapid economic growth (A1B out to 2030). Biomass burning trends are mostly positive, with significant emissions reductions expected in South and West Africa, but South American forests remain vulnerable in the A1B future.

Bringing SO_2 emissions into the picture reveals with even greater clarity the key role of China. China's SO_2 emissions may range widely between an increase of 21,000 Gg and a decrease of 30,000 Gg, each endpoint having quite different BC and OC characteristics. It is interesting to note that rather similar endpoints are reached for aerosol emissions under the contrasting A1B and A2 scenarios. General increases in aerosol emissions can occur if either economic growth outstrips environmental protection (A1B) or economic growth is inhibited and technology transfer stagnates (A2). When we combine all three species together, clear signals emerge for East Asia, South Asia/South America, Japan, and the Middle East/North Africa, which may be helpful in designing mitigation measures at global scale that will guide us down environmentally advantageous future pathways of energy and economic development.

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