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Linking future aerosol radiative forcing to shifts in source activities

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[1] We model future direct radiative forcings of the major anthropogenic aerosol species, sulfate, black and organic carbon, within industrial, power, transport, and residential sectors and biomass burning. A sectoral perspective helps to inform mitigation directions. More accurate projections are facilitated by recent carbonaceous aerosol emission estimates that incorporate projected technology changes, now available for the Intergovernmental Panel on Climate Change scenarios A1B and B1, for 2030 and 2050. Net present-day model anthropogenic forcing is -0.11 W m^{-2}. By 2050 this doubles (A1B) or drops by 30% (B1), depending mostly on sulfate changes in the industry and power sectors. Present-day (non-biomass burning) BC forcing comes mostly from residential sources (+0.09 W m^{-2}), however this is projected to decrease by more than a factor of 10 by 2050. Future BC forcing is projected to come mostly from transport, changing from +0.06 W m^{-2} in 2000 to +0.04 (B1) or +0.07 W m^{-2} (A1B) by 2050. **Citation:** Koch, D., T. C. Bond, D. Streets, and N. Unger (2007), Linking future aerosol radiative forcing to shifts in source activities, *Geophys. Res. Lett.*, *34*, L05821, doi:10.1029/2006GL028360.

1. Introduction

[2] Aerosol particles resulting from burning of fossil fuel and biomass are believed to have a net negative radiative forcing and cooling effect on the climate, thus partially offsetting warming from increased greenhouse gas emissions. Inefficient combustion of these fuels can generate dark particles or 'black carbon' (BC) that also absorb incoming solar radiation, exert a positive radiative forcing, and may thus contribute to warming. It may be possible to combat global warming by targeting emissions of BC. Such a strategy requires a perspective that links radiative forcing to specific emission source types, or sectors, for present and projected scenarios.

[3] Indeed future aerosol impacts on climate depend upon fuels burned and technologies used in various energy-related activities. Actions that occur because of economic growth, or the desire to mitigate climate effects or improve air quality, affect all aerosols. Thus as we consider various future climate scenarios, it is logical to view them as a function of activity, or sector. The sectors we consider are industry, power, transport and residential sectors, as well as biomass burning and natural sources. Each sector has a different composition and effect on the radiative budget. We simulate three major aerosol components, sulfate, black and organic carbon, distinguishing among emission sectors, in a global climate model. *Koch et al.* [2007] showed that in the present, the industry and power sectors have negative radiative forcing due to large sulfate content; the residential and transport sectors have net positive forcing because they have more BC. Here we consider how these sectoral climate forcings change for two established future scenarios.

[4] Realistic projections of future aerosol radiative forcing require emission projections that incorporate technology changes, such as particle traps, since these can greatly reduce primary aerosol emissions. Such SO_2 emission projections have been available, e.g., from the IPCC SRES scenarios [*Intergovernmental Panel on Climate Change* (*IPCC*), 2000]. However until recently, carbonaceous aerosol emission projections failed to incorporate anticipated development of emissions controls and therefore probably over-predicted future emissions. Thus, previous carbonaceous aerosol emission projections assumed proportionality to CO [e.g., *IPCC*, 2001] or CO_2 [e.g., *Takemura et al.*, 2001] and predicted large increases in carbonaceous aerosol amounts. However, the proportionality between CO and carbonaceous aerosol emissions is not exact; and CO_2 emissions are dominated by sources including power generation, heat and electricity for industry, and vehicles of all types, while carbonaceous aerosols come preferentially from particular sources such as diesel engines and biofuel burning. Recently, future carbonaceous aerosol emissions that include technology effects have been developed for some of the IPCC SRES scenarios [*Rao et al.*, 2005; *Streets et al.*, 2004].

[5] A global model simulation allows investigation of the spatial patterns of impacts due to emission changes. However in some cases it is desirable to have a quick estimate of how emission changes affect global mean radiative forcing. We use our model and the future scenarios to test the degree to which future direct radiative forcing is proportional to emissions change. Proportionality between emissions and radiative forcing would permit emissions experts and policy makers to estimate impacts of emission changes on climate without a full global climate model simulation.

2. Emissions and Model Description

[6] Our present-day and natural emissions are described by *Koch et al.* [2006, 2007]. For future emissions we use the IPCC SRES scenarios A1B and B1 [*IPCC*, 2001] for the years 2030 and 2050. Both of these scenarios assume rapid economic growth, low population growth and globalization. The A1B and A2 scenarios are primarily economically driven but the A1B is considered more realistic [*Streets et al.*, 2004]. Both the B1 and B2 scenarios include introduction of clean

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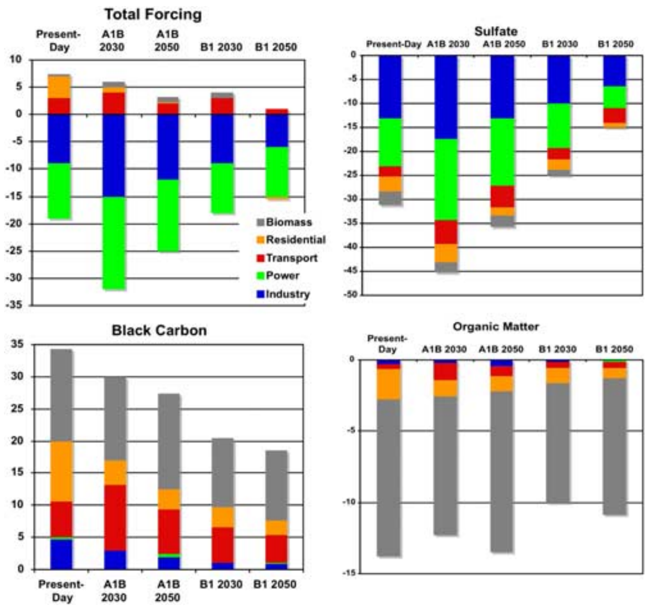

Figure 1. Radiative forcing for each species and scenario, with stacked sectoral contributions. Units are W m^{-2} $\times$ 100.

and efficient technologies; the B1 has somewhat lower emissions and therefore provides a lower bound among the SRES scenarios. Both SO_2 and carbonaceous emissions are based upon the same Integrated Model to Assess the Greenhouse Effect (or IMAGE model) SRES scenarios [*National Institute for Public Health and the Environment* (*RIVM*), 2001], hence fuel use per sector are identical. Although technological assumptions may differ between scenarios, SO_2 and carbonaceous aerosols are dominated by different sources. Thus, even different assumptions of technology will not cause great inconsistency.

[7] Our future anthropogenic SO_2 emissions came from scaling our present-day emissions by the ratio of future to present-day emissions estimated by *RIVM* [2001] SRES for each sector and region. Future carbonaceous aerosol emissions for energy sectors are from *Streets et al.* [2004]. For future biomass burning we scaled our seasonally-varying present-day emissions by the annual mean changes for each region provided by *Streets et al.* [2004]. Emissions for each sector, year, scenario and aerosol component are in Figure S1[1].

[8] The aerosol simulation is embedded in the Goddard Institute for Space Studies GCM version ModelE. Detailed descriptions of the model are published elsewhere (*Schmidt et al.* [2006] for the GCM, *Del Genio et al.* [1996, 2005] for cloud schemes, *Koch et al.* [2006, 2007], and *Koch and Hansen* [2005] for the aerosol treatment). Our present-day aerosol simulation, including analysis of sectoral impacts, is described by *Koch et al.* [2007]. Here we do not include future oxidant changes, which may cause up to 15% underestimate of future sulfate [*Unger et al.*, 2006a, 2006b]. We assume the aerosols are externally mixed and consider only direct radiative effects. We neglect climate changes associated with CO_2 changes for future and pre-industrial simulations. We do not include nitrate aerosols. Although present-day nitrate forcing is estimated to be small (-0.06 W m^{-2}) (S. E. Bauer, Radiative properties of sulfate and nitrate coated mineral dust particles, submitted to *Journal of Geophysical Research*, 2007), nitrate is projected to increase with NO_x and NH_3 [*Adams et al.*, 2001].

[9] The model results for our present-day aerosol species surface concentrations are compared with observations by *Koch et al.* [2006, 2007]. Most model concentrations agree within a factor of two of observations, except as follows. Model sulfate is a factor of 2–5 too small at many remote oceanic sites. Modeled carbonaceous aerosols are too small by a factor of 2 over southeast Asia, and are overestimated at some oceanic sites.

3. Evolution of Aerosol Optical Thickness and Radiative Forcing

[10] Present-day optical thickness for each species and sector is given by *Koch et al.* [2007, Figure 11]. Sulfate aerosol loading from the industry and power sectors are large in all major industrial regions and these loads disperse across the middle latitudes of the northern hemisphere. Natural sulfate dominates in oceanic and remote regions. Present-day BC in the northern hemisphere comes mostly from the residential sector out of southeast Asia; BC from the transport and industrial sectors are also substantial. BC in the southern hemisphere comes primarily from biomass burning. Global OM comes primarily from biomass burning, especially in the southern hemisphere. Over many regions OM is mostly natural while in southeast Asia it is primarily residential. Our present-day net anthropogenic radiative forcing is -0.11 W m^{-2}, less than the average (-0.22 W m^{-2}), but within the range (+0.04 to -0.41 W m^{-2}), of current model estimates [*Schultz et al.*, 2006].

[11] The changes in BC and sulfate optical thicknesses for each sector, scenario and year are given in Figures S2 and S3. Emissions and radiative forcing for each species, sector and scenario are given in Figure S1. Figure 1 has the global mean forcings for each scenarios. Figure 2 shows the direct radiative forcing for each sector for the present, for each 2050 scenario, and the difference between A1B and B1.

[12] Net global aerosol forcing evolution is dominated by sulfate changes in the power and industry sectors (Figure 1). In the A1B scenario, these increase while the positive residential forcing declines, so future negative forcing is more than double present-day forcing. In the B1 scenario, the power and industry sulfate decrease due largely to implementation of desulfurization technologies, so future forcing is less negative. Present-day BC forcing comes mostly from the residential sector. Both future scenarios project decreasing residential emissions due primarily to reduction in solid fuel combustion. Transport sector emissions increase in A1B or decline modestly for B1 mostly from tailpipe PM controls. Hence the transport sector is projected to become the dominant BC source. BC contributes +0.07 and +0.04 W m^{-2} to the 2050 A1B and B1 transport forcings. Net transport forcings are reduced due to the presence of scattering components.

[13] The geographical distributions of aerosol forcing shift. In the A1B, sulfate power and industry impacts

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL002720.

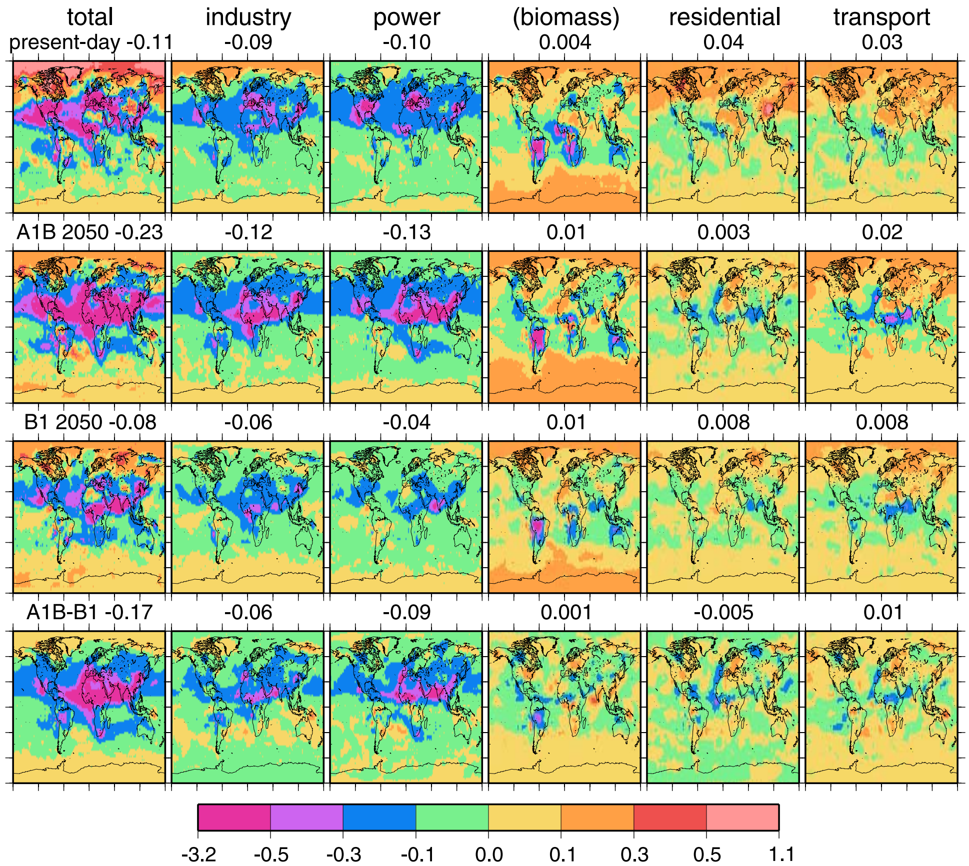

Figure 2. (left) Annual mean anthropogenic top of atmosphere radiative forcing from all energy-related (i.e. non-biomass burning) sulfate and carbonaceous aerosols and (top row) the contributions from each sector for (second row) present day 2050 A1B and (third row) 2050 B1 and (bottom row) the difference between A1B and B1 2050. Global mean is given above each panel. Units are W m^{-2}.

diminish over western Europe and North America but increase significantly over Asia, Arabia and North Africa (Figures 2 and S2). Sulfate from the transport sector also increases over south Asia and central Africa due to increased availability of vehicles in these regions. Similarly, in the B1 scenario there is a shift in industrial and power sulfate from northern industrial regions to lower-latitudes, however global sulfate does not increase as in the A1B scenario.

[14] In both scenarios, residential and industrial BC decreases, especially from Asia due largely to fuel switching. Since BC from southeast Asia tends to be transported pole-ward [*Koch and Hansen*, 2005], the Asian BC reductions cause a decrease in positive forcing over the Arctic. For both A1B and B1, BC is predicted to increase slightly across middle latitudes of the southern hemisphere, due to increased BC sources in industry, power and transport sectors. Transport sector BC increases are largest in eastern Europe, south Asia, South America and north-central Africa especially in the A1B scenario (Figures S2 and S3).

[15] Biomass burning is predicted to decrease, especially in Africa. However A1B biomass burning in South America increases, especially in 2050. In all future cases biomass burning forcing becomes more positive perhaps connected to increased burning in South America.

[16] The differences between the A1B and B1 2050 radiative forcings, shown in the bottom of Figure 2, provide an estimate of future aerosol impact uncertainty. The largest difference, globally, is in the power sector followed by industry, especially in south Asia and over central Africa where the A1B scenario indicates much more negative forcing. The transport sector has more BC in the A1B scenario and larger positive forcing in many regions, including eastern Europe, Indonesia, and South America.

[17] We use our model simulations to investigate the extent to which future radiative forcing can be inferred from emissions changes and present-day forcing. Future forcing inferred this way is:

$$F_{inf} = E \times F_{PD}/E_{PD} \qquad (1)$$

where E is future emission, F_{PD} and E_{PD} are present-day forcing and emission. In Table 1 we give $r_{inf} = F_{inf}/F$, the ratio between the inferred and model calculated forcing, for those sectors that generate at least 5% of the global emission.

[18] The inferred sulfate forcings are typically less than estimated in the full model calculations. This results from sulfate reduction between 30–60°N, where emissions decline by a factor of 1.3–3 (for A1B and B1, 2030 and 2050) and r_{inf} = 0.65–0.70. As emissions decline oxidant availability increases so that more sulfate is generated per SO_2 emitted. Coupling sulfate with chemical

Table 1. Inferred Forcing Factors[a]

Sector	SO4	BC	OM
	2030 A1B		
Industry	0.82	0.79	x
Residential	x	1.0	0.91
Power	0.87	x	x
Transport	0.63	0.87	0.51
Biomass	x	1.0	1.0
	2050 A1B		
Industry	0.78	x	x
Residential	1.0	0.93	0.73
Power	0.82	x	x
Transport	0.77	0.93	x
Biomass	x	0.97	0.97
	2030 B1		
Industry	0.85	1.6	x
Residential	0.82	1.1	0.73
Power	0.85	x	x
Transport	0.92	1.0	0.81
Biomass	1.8	1.0	1.0
	2050 B1		
Industry	0.78	x	x
Residential	x	0.96	1.0
Power	0.78	x	x
Transport	0.70	0.98	x
Biomass	x	1.0	0.9

[a]Inferred factors for sectors with emissions at least 5% of total.

oxidant changes would contribute further non-linearities [e.g., *Unger et al.*, 2006a, 2006b].

[19] The carbonaceous aerosol radiative forcing change is nearly linearly related to emission changes. Greater non-linearity would occur if our model included chemical processes such as secondary organic chemistry or coating of carbonaceous particles by sulfuric acid. However, BC forcing decline is less than inferred within the 30–60°N region, where emissions decline by a factor of 1.4–2.6 and r_{inf} = 0.90–0.96. This non-linearity may be due to saturation effects in the column absorption.

4. Discussion

[20] Future aerosol forcing for A1B and B1 SRES is controlled largely by changes in the sulfate-dominated industrial and power sectors. In these 2 sectors, by 2050 A1B sulfate forcing more than doubles from −0.23 to −0.58 W m^{-2}; the net forcing increases from −0.19 to −0.25 W m^{-2}. By contrast, the B1 scenario sulfate forcing diminishes by more than a factor of 2, from −0.23 to −0.11 W m^{-2}; the net forcing decreases from −0.19 to −0.1 W m^{-2}.

[21] Future carbonaceous aerosols are projected to decline due to fuel changes and technology improvements. These projections contrast with studies without technology changes, e.g., *IPCC* [2001] projected a 25% increase in carbonaceous aerosol load by 2030 (for the A2 scenario). Including all aerosols, *IPCC* [2001] thus projected zero (A1B) to positive (+0.04 W m^{-2} for B1) forcing by 2050. By 2050 our residential BC forcing (net residential forcing) for A1B decreases from +0.09 to +0.03 W m^{-2} (+0.04 to +0.003 W m^{-2}) and for B1 from +0.09 to +0.02 W m^{-2} (+0.04 to +0.01 W m^{-2}). In contrast, emissions from the transport sector are expected to increase or decrease only moderately. The transport sector BC (net transport) forcing for A1B 2050 increases from +0.06 to +0.07 W m^{-2} (net forcing decreases from +0.03 to +0.02 W m^{-2}) and for B1 decreases from +0.06 to +0.04 W m^{-2} (+0.03 to +0.01 W m^{-2}). Thus, while presently most energy-related BC is associated with the residential sector, future BC is expected to come primarily from the transport sector.

[22] Residential emissions appear to decline in both scenarios, a result that is largely driven by fuel-switching assumptions in SRES and technology improvements assumed by *Streets et al.* [2004]. Declines in residential carbonaceous aerosols may appear inevitable, but they rely on the capacity of affected people (frequently the rural poor) to afford improved fuels, and on the ability to improve and disseminate cooking technology, often for minimal financial returns. Both have proven to be complex problems. Furthermore, emissions from the residential sector are among the most uncertain of the energy-related sectors. It is presently estimated to be a dominant source in regions such as Asia. However model studies [e.g., *Koch et al.*, 2007; *Park et al.*, 2005] imply that emissions in this region may be too small. Thus residential emissions may be greater than the present inventories indicate. Future residential emissions may also be larger than projected in these scenarios.

[23] Because the transport sector is warming, and its forcing is substantial in both scenarios, it may offer an important opportunity to combat global warming. Note however that reducing BC from diesels appears to be quite expensive on a global warming potential basis [*Bond and Sun*, 2005]. In addition, the future of transport emissions is highly uncertain and scenario-dependent. Road traffic emissions, for example, depend upon offsetting factors of improved abatement techniques and rapid growth of vehicle usage as economies grow [*Colvile et al.*, 2001].

[24] Aerosol direct forcing effects for the SRES scenarios A1B and B1 present contrasting future impacts for air quality and climate. The A1B scenario has larger aerosol pollution loads, especially power and industrial sulfate. This scenario contains greater aerosol surface cooling at the price of poorer air quality. In contrast, the B1 scenario has reduced aerosol and better air quality. However it involves the removal of the northern hemisphere mid-latitude sulfate 'blanket' that presently reduces incoming solar radiation, thus these aerosol changes would contribute to warming especially in this region. Note that these aerosol effects are small compared with projected CO_2 forcing projections, +4.2 and +3.3 W m^{-2} for 2050 A1B and B1 [*IPCC*, 2001]. Thus the A1B scenario remains overall 'warmer' even though the estimated aerosol negative forcing is greater.

[25] Our study did not include the effects of aerosols on clouds, or indirect effects. However, we may speculate that these would compound our result: since clouds are influenced by aerosol number, and the largest aerosol mass changes are for sulfate in the power and industry sectors, we expect that the indirect effects would enhance or reduce the cooling effects of the A1B and B1 scenarios, respectively. We also anticipate increased indirect effects in the tropics and southern hemisphere, relative to today.

[26] This study is only a first step for considering sectoral impacts on climate. Future studies should include impacts of aerosols on clouds, precipitation, and ice albedo. Further-

more, gas as well as aerosol species should be included in order to understand the full impact of future sectoral changes.

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