Short-Lived Climate Forcing Agents and Their Roles in Climate Change

Gregory R. Carmichael
University of Iowa

Sarika Kulkarni
University of Iowa

Yafang Chen
University of Iowa

Please see article for additional authors.

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Abstract:

Short-lived climate forcing agents (SLCFAs) such as black carbon and ozone offer important policy opportunities to reduce radiative forcing in the short term (this decade), while also reducing air pollution impacts. Because of the combination of high absorption, a regional distribution roughly aligned with solar irradiance, and the capacity to form widespread atmospheric brown clouds in a mixture with other aerosols and ozone, emissions of black carbon are the second strongest contribution to current global warming, after carbon dioxide emissions. The interception of solar radiation by atmospheric brown clouds leads to dimming at the Earth’s surface with important implications for the hydrological cycle, and the deposition of black carbon darkens snow and ice surfaces, which can contribute to melting, in particular of Arctic sea ice. Reducing SLCFAs is a challenge as they are emitted and produced across a wide spectrum of source-sectors. In this paper we summarize our capabilities to predict the impacts of short-lived forcing agents, and their local, regional and global extents, building upon studies done in Asia. We also discuss possible policy measures for reducing them.

1. Introduction

High aerosol loadings are prevalent throughout the atmospheric environment in many parts of the world. This rich mixture of aerosols and their precursors comprise what is commonly referred to as Atmospheric Brown Clouds (ABCs). The anthropogenic component of ABCs consists of primary particles and secondary aerosols produced from chemical reactions involving pollutant gases, such as nitrogen oxides, sulfur dioxide, ammonia, ozone and hundreds of organic gases and acids. Widespread ABCs result from the combustion of biofuels used in cooking and heating, open biomass burning, and fossil fuels used broadly throughout diverse economic sectors. These aerosol components and gas phase pollutants such as ozone are major air pollutants and also important short-lived climate forcing agents. Black carbonaceous aerosol (BC) is a particularly important component of atmospheric particles because of its dual roles in health and climate. BC contributes significantly to surface mass concentrations of fine particulate matter.
(PM$_{2.5}$), exposure to which is linked to increased mortality and pulmonary disease (e.g., Pope et al., 2002; Schwartz et al., 2008). In addition, BC is a strong short-lived climate forcing agent. Through its direct absorption of incoming shortwave radiation, BC is estimated from models and observations to have a global direct radiative forcing within the range of 0.2 to 1.2 W/m$^2$ (Forster, 2007; Ramanathan and Carmichael, 2008). Its efficacy as a climate forcer is also very high when deposited on snow (Hansen et al., 2005). These aspects combined have made BC a target for mitigation efforts with health and climate co-benefits (e.g., Jacobson, 2002; Bond, 2004; Unger et al., 2010). Yet, the potential impact of BC emissions reductions on climate may be counteracted by the degree to which the potential for co-benefits is modulated by co-emission of BC with reflective, cooling, aerosol (Aunan, 2009; Bauer et al., 2010; Chen et al., 2010; Ramana et al., 2010). These issues underscore the need to improve our understanding of the distributions and impacts of BC and other SLCFAs.

Models play a critical role in linking emissions through to climate and environmental impacts. The chain of analysis is illustrated in Figure 1, where emissions are used in chemical transport models (CTM) to produce 4 dimensional distributions of SLCFA, which are in turn used to drive radiative transfer models (RTM) and climate models (CM) to produce climate responses and to assess impacts. The power of this chain of analysis is that it enables the study of changes in impacts (metric) of interest with respect to changes in sectoral (e.g., power, industry, residential, transport) emissions. This information is needed to help inform policies that target reductions in health and climate impacts. However, considerable deficiencies persist in our ability to model, and hence understand and regulate, BC and other SLCFAs. Black carbon simulations over the U.S. show many obvious shortcomings, including high biases in winter, poor representation of the urban excess, limited skill in representing temporal variability, and obvious emissions biases (e.g., Spak and Holloway, 2009). While resolving the basic seasonality of BC, daily time series comparisons with surface measurements vary dramatically; at times models are only capable of explaining a fraction of the observed variability (Spak and Holloway, 2009). Models lack processes for resolving important differences in the transport of these species; large-scale transport processes affecting rural areas are better simulated than local emissions and dispersion from urban areas, while temporal relationships in between BC, OC, and total fine particle mass in regional models were stronger than in observations. Additionally, a significant fraction of the uncertainty in regional BC simulations is due to variability in modeled particulate aging and wet deposition.

Issues in the basic simulation of BC become more pronounced when turning to global-scale simulations of concentrations and absorption. The emissions inventories themselves are recognized to have 50% uncertainty in global totals, and have estimated errors of a factor two to five in specific regions (Bond et al., 2004; Ramanathan and Carmichael, 2008). Further, recent work (Koch et al., 2009) has highlighted significant, and at times conflicting, discrepancies between the accuracy of BC mass concentrations vs biases in estimating total column absorption, demonstrating that present models lack skill in representing BC vertical distributions and microphysical properties. Consequently, models have large uncertainties in the net climate forcing from BC (Bauer et al., 2010; Chen et al., 2010). These limitations collectively lead to large uncertainties in attributing BC and its radiative forcing to specific economic sectors (e.g. Unger et al., 2010) at the level of spatial specificity needed for targeted policy action, especially when isolating the effects of BC from co-emitted gas and aerosol species.

2. Reducing Uncertainties

We need to reduce the uncertainties in the analysis chain described above. Uncertainties are reduced through laboratory and field experiments that improve our understanding of key processes and provide data to help constrain model predictions. For example, constraining modeled aerosol distributions through the use of remotely sensed information on aerosol optical depth and single scattering albedo has been shown (Adhikary et al., xxxx; Chung et al., 2010) to produce distributions that are much closer to observations. Example results are shown in Figure 2 for Asia, where constrained annual mean surface
distributions of dust, BC, sulfate and total PM$_{2.5}$ are shown. Sulfate and black carbon are significant components of Asian aerosols. They play an important roles both in health and climate impacts. BC absorbs radiation and thus is a SLCFA that warms the climate; while sulfate scatters incoming radiation and acts to cool the climate and mask the warming caused by the greenhouse gases. The sulfate distribution shows the highest concentration in the Indo Gangetic plain and East China. These regions are highly populated areas with substantial fossil fuel consumption (largely coal), which leads to high sulfate concentrations. In contrast, the BC distribution has high values extending into more rural regions, as shown in southern India and SE Asia. This reflects the fact that BC has diverse emission sources including biofuels, open biomass burning and fossil fuel sectors. Wind blown dust is a significant source of particles throughout much of Asia during dry seasons. While the bulk of the dust emissions occur in the coarse-mode, the fine-mode emissions are also appreciable and contribute to the PM$_{2.5}$ levels in and downwind of the desert regions of China and Western Asia.

An immediate value of the observationally constrained estimates of BC mass is to reduce uncertainty in estimates of health impacts such as human mortality (Carmichael et al., 2009). The high aerosol levels in Asia have a direct impact on human health. Figure 2 shows the population weighted exposure to PM$_{2.5}$ levels greater than the WHO annual guideline of 10 g/m$^3$ (for grid cells with concentrations > 10 g/m$^3$ the PM$_{2.5}$ concentration is multiplied by the population in that grid using annual population from the Gridded Population of the World Version3 [GPWv3] available at http://sedac.ciesin.columbia.edu / gpw). Over 3 billion people in Asia live in areas that exceed the WHO annual guideline for PM$_{2.5}$. This may represents a conservative estimate of exposure as seasonal exposure levels can be significantly higher than the annual mean values, and sub-grid concentration “hot spots” also exist that can not be represented by the grid spacing used in the present simulations. The result shows that the Ganges Valley in India, the Pearl River Delta and Eastern China regions, and the Asian megacities are primary hotspots for PM exposure. Recently these data have been used by health specialists in Asia to estimate the health impacts due to exposure to these levels of aerosol (Ramanathan et al., 2008). Using concentration response relationships from the existing literature, it is estimated that exposure to each increase in anthropogenic PM2.5 of10 g/m$^3$ results in ~165,000 excess deaths per year in India and China, with a 95 per cent confidence interval of 90,000—250,000. This outdoor exposure risk is in addition to a WHO estimate of 381,000 and 407,000 for China and India, respectively, from indoor air pollution caused by solid fuel use.

BC is of particular interest from a climate perspective as it is an absorbing aerosol and thus contributes to warming (BC warming potential is ~ 55% of that due to CO$_2$ [ top of the atmosphere forcing of BC is +0.9 vs. +1.6 W/m$^2$ for CO$_2$ ], Ramanathan and Carmichael, 2008). Collectively ABCs have given rise to major areas of concern, some of the most critical being the observed decrease in the Indian summer monsoon rainfall, the north-south shift in eastern China rainfall patterns, and the accelerated retreat of the HKHT glaciers and decrease in snow packs. All these have led to negative effects on water resources and crop yields in Asia (Ramanathan et al., 2007).

The observational constraints for the SLCFA aerosol distributions when used to estimate BC direct radiative forcing (Chung et al., 2010), produced values that are at the upper end of current radiative forcing estimates (0.9 W/m$^2$). The presence of absorbing aerosols alters net surface radiation, latent and sensible heat fluxes (Dennem et al., 2007), which, depending upon the altitude of the aerosols, can either increase or decrease cloud fraction (semi-direct effect ; Grassl, 1975) and atmospheric stability (e. g., Penner et al., 2003, Grell et al 2010).

3. Policy Implications

The wide-ranging impacts of SLCFA's strongly suggest that reducing aerosol emissions can contribute to multiple environmental improvements. From the health perspective, reducing PM$_{2.5}$ levels will greatly reduce excess mortality and morbidity due to air pollution. From the climate change perspective, aerosols currently play an important role in masking the true impact of the greenhouse gases. Thus to minimize the
impacts of GHGs it is desirable to change aerosols in the future in a manner that maximizes the net cooling (masking) effect of SLCFAs (i.e., by decreasing the absorbing to scattering ratio in ABCs). Thus strategies to meet this goal should consider the effect of ABC composition on climate response. A win-win strategy is to reduce ABCs (thus decreasing the health impacts) in a manner where absorbing aerosols decrease more rapidly than the scattering components (thus minimizing the warming). This requires the identification of emission reduction strategies that preferentially reduce BC emissions. Furthermore, as discussed in Raman et al. (2010) and Ramanathan and Carmichael (2008), BC from different source sectors have different absorption properties (e.g., BC from fossil fuel sources are stronger absorbers than those from biomass burning sources). As BC is emitted along with other aerosols and aerosol precursors, the effectiveness of reduction in BC from a climate perspective depends strongly on the ratio of absorption to scattering. We have proposed that the BC to Sulfur (BC:S) ratio is one metric that captures this relationship, such that effective strategies from air pollution and climate perspectives would be those that reduce both the BC mass in the atmosphere and the ratio of BC to sulfate.

It is important to analyze sector based contributions to impacts, as emission control measures will be developed by sector and not by species. We have calculated the sector base contribution to predicted BC and sulfate surface concentrations for various locations in Asia (Figure 3). These results show that the sectoral contributions to sulfate and BC aerosols differ significantly, with sulfate dominated by power and industrial sources that utilize coal. Biofuels used for domestic purposes (cooking and heating) currently are the largest source of BC in South Asia, and play a significant role in Southeast and East Asia. Fossil fuel sources (industrial and transport uses) are the major contributors to BC in China. The contribution of biofuels to surface concentrations can be larger than that shown. For example, over the Indian subcontinent the contribution of biofuels to surface BC can reach 70% -90% while the values range from 20% -80% over China. The aggregate national emissions of BC and sulfur dioxide are comprised of the contributions from all the sectors, and the total emissions as well as the ratio of BC: S in the emissions vary between countries depending on the sectoral importance, and how they change over time.

We examined the trend in BC:S in the emissions and in the calculated ambient aerosol in Asia for the period 2000 to 2008 (Figure 4). The emission inventory estimates indicate that while emissions in India and China have increased significantly during this period, the BC:S ratio in China has remained fairly constant, while in India it has deceased. Also shown are the BC:S ratio for the fossil portion of the inventories, which show that the ratio is significantly lower in the fossil component than in the total emissions.

To see how PM$_{2.5}$ and the relative amounts of BC and sulfates may change in Asia by the year 2030 we performed simulations using the A1B, A2, B1 and B2 scenarios from IPCC defined development pathways. Each of these simulations were done for a single year using 2004 meteorology and results compared to the 2004 simulations using the base emissions. Figures 5a and 4b show the changes in PM$_{2.5}$ concentration at the surface layer in two future scenarios. These results show the influence of changes in emissions. In the A1B emission scenario the domain-wide BC and SO$_2$ emissions relative to the base case changed by -30% and +130%, respectively. This scenario shows an annual increase of PM$_{2.5}$ mass concentration of more than 15 μg / m$^3$ over the highly populated Ganges valley and eastern China regions. Significant increases in aerosol mass are also found in outflow regions as seen over the Bay of Bengal and the East China Sea / Pacific Ocean. The B1 emission scenario (with domain-wide BC and SO$_2$ emissions changes of -50% and +12%, respectively, relative to the base case) also shows an increase in aerosol mass over much of South Asia, but only a slight increase over China. In both of these scenarios, the health impacts of ABCs would increase.

The ratio between BC and sulfate AOD over Asia for the current year is shown in Figure 4d. The areas with the highest BC to sulfate ratios are those with large contributions of biofuels and open burning, e.g., South and Southeast Asia, because biofuel sources have much higher BC than sulfur emissions. In the A1B, B1 and B2 scenarios, the BC from biofuels decrease significantly (see Figure 4e); however only for the B1 and B2 scenarios do the total BC levels in Asia decrease. The BC to sulfate ratio is shown for
present and future emissions in Figure 4f for three megacities in Asia that have different emission source profiles. Model simulations show that for both A1B and B1 the BC to sulfate ratios decrease compared to the base year; however, only B1 shows a significant decrease in BC mass as well.

These future scenarios show that there are ways to decrease the BC contribution to ABCs. Targeting biofuel reductions is a key strategy and has the added benefit of reducing indoor levels of carbonaceous aerosol, dramatically decreasing human exposure. Controls focused on diesel emissions from vehicles are also an important target for BC emission reductions. Unfortunately, these future scenarios still show an increase in PM$_{2.5}$ levels due to increases in energy consumption and continued reliance on coal with attendant increases in SO$_2$ emissions.

However, there are ways to reduce both BC and sulfate. For example, a variety of emission reductions measures were put into place for the recent Beijing Olympics. These included permanent measures (e.g., improved quality of transport fuels, closing of some industries) as well as temporary ones (e.g., banning cars from use on certain days, halting of construction). Our preliminary analysis suggests that these measures reduced emissions of both SO$_2$ and BC in the region, and that the BC:S ratio was also reduced (as shown in Figure 4). There are lessons to learn from these efforts, and clearly more work is needed to identify possible actions focused on SLCFAs that can improve both health and climate impact, as both must be considered when identifying mitigation targets.

References


Figure 1  Schematic of the analysis chain that links sectoral emissions through atmospheric transport, radiation and climate models to produce estimates of impacts.
Figure 2 Four year optimally constrained surface distributions of Sulfate, BC and fine mode dust (\(\mu g / m^3\)), and population weighted exposure to PM\(_{2.5}\) levels greater than the WHO guideline of 10\(\mu g / m^3\) (for grid cells with concentrations > 10\(\mu g / m^3\)), the PM\(_{2.5}\) concentration is multiplied by the population in that grid using annual population from the Gridded Population of the World Version 3.

Figure 3 Dry season mean surface concentrations of BC and sulfate along with emission sector contributions at various locations in Asia for year 2006.
Figure 4  BC to sulfur ratios for emissions from all sources and fossil fuel sources in India and China for various years. Simulated mass ratios of surface BC and sulfate concentrations are also shown.
Figure 5  The change in surface layer PM$_{2.5}$ concentration from the year 2030 to the base year via IPCC A1B emissions pathway (a); B1 emissions pathway (b); Carbonaceous aerosols (from bio-fuel emissions alone) contribution to AOD (c), modeled BC / SO$_4$ AOD (d), and regional average BC column concentration ($\mu$g / m$^2$) illustrating the sectoral contribution (e) and ratios of BC / sulfate column loadings from base and projected future emissions at selected megacities (f).