Can warming particles enter global climate discussions?

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Abstract

‘Soot’ or ‘black carbon’, which comes from incomplete combustion, absorbs light and warms the atmosphere. Although there have been repeated suggestions that reduction of black carbon could be a viable part of decreasing global warming, it has not yet been considered when choosing actions to reduce climatic impact. In this paper, I examine four conceptual barriers to the consideration of aerosols in global agreements. I conclude that some of the major objections to considering aerosols under hemispheric or global agreements are illusory because: (1) a few major sources will be addressed by local regulations, but the remainder may not be addressed by traditional air quality management; (2) climate forcing by carbon particles is not limited to ‘hot spots’—about 90% of it occurs at relatively low concentrations; (3) while aerosol science is complex, the most salient characteristics of aerosol behavior can be condensed into tractable metrics including, but not limited to, the global warming potential; (4) despite scientific uncertainties, reducing all aerosols from major sources of black carbon will reduce direct climate warming with a very high probability. This change in climate forcing accounts for at least 25% of the accompanying CO2 forcing with significant probability (25% for modern diesel engines, 90% for superemitting diesels, and 55% for cooking with biofuels). Thus, this fraction of radiative forcing should not be ignored.

Keywords: particles and aerosols, impacts of climate change, effects of aerosols, climate policy

1. Introduction

Activities that produce greenhouse gases also result in aerosols (suspended particles), ozone, and carbon monoxide. Although their atmospheric lifetimes are far shorter than those of greenhouse gases, these species alter the Earth’s radiative balance, either directly or through atmospheric chemistry. Most aerosols, including sulfates and the light-colored organic carbon, offset and mask the warming effects of greenhouse gases by reflecting light. The dark aerosol known as black carbon absorbs light and warms the atmosphere. The perturbations caused by both greenhouse gases and aerosols are often quantified in terms of radiative forcing—the change in energy balance at the top of the troposphere. For some combustion sources, short-lived species contribute to or offset a portion of the radiative forcing. In this paper I focus on black carbon and its potential contribution.

There has been no shortage of scientific discussions on the role of aerosols in climate policy. West et al (1997) averred that climate policy could not ignore aerosol emissions. The ‘alternative scenario’ of Hansen et al (2000) included both short-lived species and traditional greenhouse gases in a climate management portfolio. Holloway et al (2003) suggested that agreements focusing on transboundary pollution could address short-lived species. Rypdal et al (2005) outlined the scientific and political hurdles to be overcome for inclusion of such species in climate accords. Bond and Sun (2005) suggested that addressing black carbon could be an economical way to reduce climate impact for some sources. Hansen’s counsel to consider black carbon and ozone in climate mitigation has been echoed by others, most recently the Scientific Expert Group on Climate Change (SEG 2007). Such actions are promising, not only because they could be economical, but also because they could reduce climate forcing rapidly, buying time to develop greenhouse-gas reductions.

The vast majority of organizations responsible for quantifying greenhouse-gas emission reductions and selecting mitigation projects are either unaware of the forcing contributions of other species or they disregard these contributions. There are practical reasons: no credit is
given for such species under the present Kyoto Protocol, and thus no reward accrues for including the additional complexity. Ignoring a portion of radiative forcing, however, can result in misinformation about the net benefits of chosen actions. For example, some CO2 mitigation measures also reduce cooling aerosols, and would reduce positive radiative forcing less than expected (e.g. Smith et al 2000a, BERNSTEN et al 2006). Smith et al (2000b) observed that minimizing traditional greenhouse gases (CO2, methane, and nitrous oxide) by choosing renewably harvested biofuel instead of fossil fuels could actually increase total radiative forcing if the products of incomplete combustion were counted. ‘The policy implications’, they wrote, ‘...are profound’. JACOBSON (2002) reported a similar dissonance in choosing vehicle fuels: diesel vehicles produce less carbon dioxide, but may cause more positive radiative forcing if black carbon particles are counted.

In summary, scientists agree that aerosols and other short-lived species affect climate. Some go so far as to say that they are worth considering in climate mitigation strategies. However, in current practice for evaluating actions and making decisions, their effects are ignored. What causes this gap? In this paper I examine four conceptual barriers to considering and quantifying carbon particles in global agreements. These obstacles are often raised in policy-relevant discussions, but are not addressed in the scientific literature, which tends to focus on detailed aerosol physics and climate response.

(1) Carbon particles will soon be addressed by local regulations. Therefore, they should not be considered in global or hemispheric agreements, which focus on pollutants that would not otherwise be addressed by local control.

(2) Carbon particles have primarily local effects. Therefore, it is inappropriate to consider them in global regulations.

(3) Aerosols are too complex to address in discussions on climate mitigation. The intricacies of aerosol physics and chemistry preclude discussion by non-experts.

(4) The climatic effects of black carbon are highly uncertain. Quantifying and acknowledging their impacts must wait until more certainty is in hand.

2. Will carbon particles soon be addressed by local regulations?

If local regulations are the most effective way of addressing carbon particles, including those species in global agreements may be unwise. Here, I identify major emitters, and discuss likely reductions in the light of history or upcoming regulations. I rely on a global emission inventory in which emissions are estimated by combining fuel use, technology-specific emission factors, and technology differences between regions (Bond et al 2004). Data used here are updated from the earlier work with year-2000 energy data and the biofuel tabulation of Fernandes et al (2007). Global emission inventories are notoriously uncertain; knowledge including real-world emission factors, combustion types, and total fuel quantities in some sectors is lacking. The presentation should be taken as qualitative rather than definitive.

2.1. Major sectors

Figure 1(a) shows per-capita black carbon emissions from energy-related combustion (which excludes open vegetative burning) in 17 world regions. Figure 1(b) summarizes global emissions of both black and organic carbon, including the contribution of open burning. Colors indicate the economic sector producing the emissions: purple is electricity generation or industry, orange is transport, and blue is residential or commercial. There are a few notable differences among regions. Where coal is burned in the residential sector, it boosts per-capita total emissions. ‘Other’ residential emissions are usually middle-distillate fuel burned either in generators or in boilers. High industrial emissions in East Asia include the contribution of coke-making for the steel industry. North America probably has higher emissions from transport because of the longer distances required to convey goods. The figures illustrate the following points:

(1) Per-capita emissions are within a factor of three between all regions, regardless of development level. Black carbon emissions do not vanish as incomes rise, and no region can be considered clean. Although significant reductions in per-capita emissions have occurred in individual countries, increased fuel consumption offsets some of the improvements.

(2) Major decreases in global black carbon loading will only be possible by addressing five major sources: on-road...
Figure 2. Fraction of emissions attributable to superemitting vehicles. O indicates central estimates of superemitter fractions, and X indicates uncertainties. A discussion of emission rates and superemitter fractions is given in Bond et al. (2004).

2.2. Large sub-sectoral contributions

Sectoral averages like those in figure 1 can bury the large contribution of small fractions. As an example, figure 2 shows the contribution of ‘superemitters’—poorly tuned vehicles—to total emissions. In one scenario, vehicles are relatively clean and superemitters comprise 5% of the population. In the other scenario, normal vehicles have higher emissions and poorly tuned vehicles form a larger fraction of the population, namely 20%. Superemitting vehicles might contribute nearly half of the vehicular emissions in either case, as is common to many locations (Zhang et al. 1995).

Figure 3 demonstrates heterogeneity for four of the major emitting sectors, again drawing data from the year-2000 emission inventory depicted in figure 1. For clarity, only central values are shown here. Note that the substantial variability among apparently identical sources is not represented; for example, superemitters are identified separately, but differing levels of repair among ‘average’ vehicles are not. A local inventory which identified more separate sources would result in smoother curves.

When sources within a sector are dissimilar, emissions could be either easier or harder to mitigate than those from a homogeneous sector. In a sector with little variation, cleaning up any source yields similar results, actions need not target specific emitters, and policies may be easier to formulate. Residential biofuel is an example of a relatively homogeneous sector. Most of the emissions come from sources with similar characteristics. Europe, where biofuel is burned in apartment building stokers as well as small stoves, is less homogeneous. Both residential and industrial coal sectors are heterogeneous. High-emitting fractions are composed of coal for individual households in the residential sector, and small boilers and coking coal in the industrial sector. Emissions from heterogeneous sectors might be attractive targets for mitigation if high emitters can be identified and addressed at a lower cost than other sources in the sector. However, they might be harder to target if high emitters evade detection.

Air-quality rules have certainly addressed some prevalent sources such as power plants and current-model vehicles, producing the high, relatively clean tails in figure 3. If the remaining sources are outside areas of high population density, urban management may miss them. There are also key differences between management of urban air quality and management of global or regional atmospheric health. In urban management, polluters are often penalized, discouraging high polluters from coming forward. Mechanisms that protect regional air quality (such as those addressing acid rain) or reduce climate impacts (such as the clean development mechanism) may place a value on emissions, providing incentives for polluters to identify themselves.

I set out to answer the question of whether local regulations would soon ameliorate the emissions that affect climate. At least three major sources—residential solid fuels, off-road diesel, and open vegetative burning—are not addressed in countries’ first air-quality regulations. Important fractions of the other two sectors—industrial coal and on-road diesel vehicles—may be missed as well. The assumption that urban management will reliably address these sources in the near future is questionable at best.

3. Do carbon particles have primarily local effects?

The global spread of carbon particles has been modeled for over a decade (Haywood et al. 1997, Penner et al. 1998). Bergin et al. (2005) review models and measurements that demonstrate long-range transport of aerosols. Koch et al. (2007) found that 65–90% of industrial aerosol is transported beyond the boundaries of emitting regions. However, because aerosols have short atmospheric lifetimes, high concentrations of primary (directly emitted) species occur near sources. Contour maps showing such ‘hot spots’ are sometimes used to demonstrate that carbon particles have only local effects. This is a misconception. High near-source concentrations do not imply that distant effects are negligible.

I first illustrate this concept using single-source groups in selected countries. These groups included biofuel emissions in Honduras and Tamil Nadu (India), and diesel emissions in Thailand. These groups were chosen to depict relatively small areas and to examine different geographic and meteorological conditions. I then used each emission distribution as an
4. Are aerosols too complex to address in discussions about climate mitigation?

4.1. Simple metrics

The possibility of quantifying how individual actions affect radiative forcing implies that this analysis could be accomplished by non-scientists. In fact, the complexity is daunting. Regional meteorology, particle microphysics, and chemical reactions contribute to uncertainties. How can practitioners without a detailed knowledge of aerosol science move forward in the face of this complexity?

I suggest that scientists can condense their hard-won understanding into tractable metrics, as shown in figure 5. The pathway along the bottom of the figure is similar to that presented by Fuglestvedt et al (2003). Here, I have added the simple metrics needed to express the relationships between calculation steps. These are emission factor (which is already widely used), lifetime, normalized forcing, and climate sensitivity. The idea of using such metrics is not new. Both the Intergovernmental Panel on Climate Change (Ramaswamy et al 2001) and Schulz et al (2006) compared model outputs using normalized forcing, while Textor et al (2006) compared aerosol lifetimes.

This is not a call to oversimplify the aerosol system. Aerosol lifetime is an easily understood concept, but complex simulations of transport and chemistry are required to calculate...
4.2. Impacts of an emission increment

A comment on incremental versus total forcing is in order. Significant efforts have been expended to quantify total aerosol forcing, including several major field measurement programs and satellite missions. This effort greatly advances present-day understanding of the atmospheric chemical system. Incremental forcing may be thought of as $\frac{\delta F}{\delta E}$, the change in forcing with respect to a change in emissions. If forcing is linear in emissions, this quantity is a constant.

For two critical policy-relevant questions, incremental forcing is more important than total aerosol forcing. The first question is the value of climate sensitivity, or temperature response to unit forcing. This sensitivity can be inferred by comparing modeled climate forcing with the temperature record over several decades (e.g. Andronova and Schlesinger 2001). Knowledge of total present-day aerosol forcing is insufficient for this comparison. Of greater importance is identifying how forcing has changed over time. The second question is what future climate one might expect, given an emission pathway. Observations or models of present-day aerosol forcing cannot provide this answer, either. Both climate sensitivity and future climate require the estimation of (1) emission time trends and (2) changes in forcing that correspond to these emission changes. Present-day forcing constrains these only indirectly.

Incremental forcing may also be used to answer the question: what changes in climate might be expected from any particular action? Such an appraisal could support decisions for mitigating climate effects. Assuming that aerosol physics, chemistry, and optics are known within desired uncertainty, the radiative effects of a single action can be estimated without knowing total aerosol forcing.

4.3. Global warming potential and its relationship to simple metrics

Under the Kyoto Protocol, actions are evaluated with the 100-year global warming potential (GWP), an incremental measure. The GWP is an accepted simple metric that can be used in policy discussions, and that incorporates some of the metrics outlined in figure 5. It is used to compare the radiative effects of different species by comparing the warming by some substance of interest with that of carbon dioxide:

$$\text{GWP}_s = \frac{\int_0^\tau r_s(t) a_s(t) \, dt}{\int_0^\tau r_{CO_2}(t) a_{CO_2}(t) \, dt} \quad (1)$$

where $\tau$ is the time frame of interest, $a$ is the radiative forcing per mass, $r$ is the atmospheric burden after a unit-mass pulse injection, and the subscripts $s$ and $CO_2$ refer to the substance of interest and $CO_2$, respectively. The equation relates directly to the simple metrics in figure 5. Lifetime is another way of representing the time-dependent burden $r(t)$, and $a$ is normalized forcing.

Table 1 summarizes metrics that have been used to evaluate warming. While some differ from the definition in equation (1), they are all of similar magnitude. Values from Jacobson (2005) and Berntsen et al (2006) are lower than the other two by factors of three to four. The simple metrics outlined in section 3 can provide insight into such differences. For example, Bond and Sun (2005) showed that normalized
forcing calculated by Jacobson (2002) was half that of other studies. Berntsen et al (2006) used lower absorption and normalized forcing, because they ignored black carbon mixing with other species.

The global warming potential is not perfect, and has been scrutinized extensively elsewhere (e.g. Harvey 1993, Smith and Wigley 2000, Fuglestvedt et al 2003). It is controversial for short-lived species, for which the temperature response to a pulse change differs from the response to a step change (Shine et al 2005). Prather (2002) showed that atmospheric burdens normalized to total emission were identical for either an emission pulse or sustained emissions. (This fact probably explains the similarity between the Bond and Sun (2005) and Berntsen et al (2006) values.) Even if a measure other than the global warming potential becomes accepted, lifetime and normalized forcing will greatly affect it, and will probably be used to as direct inputs to the calculation.

In summary, a few scientists are estimating global warming potentials, and even more use lifetime and normalized forcing for model comparisons. The latter measures can also communicate the implications of improved understanding of aerosol science. For example, Stier et al (2006) showed that interactions between different aerosol species affect aerosol lifetime. The relevant contribution of aerosols, then, is not too complicated to communicate using simple metrics.

5. Is our knowledge about aerosols too uncertain to quantify actions?

Even if simple metrics can be accepted, many gaps in our understanding of aerosols remain. Uncertainty in the physics, chemistry, and optics of these particles is often given as a reason to ignore their climatic impact. Here, I employ aerosol lifetime and normalized forcing from three-dimensional model studies to constrain a simple model, and then use that model to examine these uncertainties.

5.1. Two-box model

I developed a simple, time-dependent model with two boxes: a ‘surface’ box into which emissions are injected and an ‘aloft’ box. I chose these two boxes because models show that forcing by an absorbing aerosol is quite sensitive to the amount of aerosol above the clouds. Table 2 summarizes the inputs to this model, their uncertainties, and the source of data.

The amount of black and organic carbon from burning 1 kg of different fuels was released into the surface box. The total removal rate from the system was set using aerosol lifetimes from AEROCOM, a recent aerosol model intercomparison effort (Textor et al 2006). Model variability is not a complete measure of uncertainty, because many models have similar parameterizations. I increased the uncertainty in overall lifetime above that reported by AEROCOM using two sources: my own runs of CAM in which wet removal parameters were varied, and results from similar published sensitivity studies (Koch 2000, Cooke et al 2002). I estimated the difference between the total removal rate and the removal rate in the surface box by comparison with a ‘normal’ CAM run and a run in which convection was turned off, preventing aerosol from being transported aloft. Lifetime near the surface was about 1 day shorter than the lifetime in the entire system. Finally, removal rates from the box aloft were set so that the fraction of mass aloft corresponded to that from AEROCOM models.

Optical properties (scattering and absorption) per mass include the effects of microphysical parameters such as particle size. The treatment of scattering by organic carbon includes increases due to hygroscopic growth. Clear-sky forcing is calculated using the one-dimensional forcing equation given by Chylek and Wong (1995), and the same relationship is used to determine forcing by aerosol above clouds. The average normalized forcing for uncoated black carbon predicted by the two-box model (1100 W g⁻¹) is similar to, but slightly lower than, models summarized by Ramaswamy et al (2001, 2002). I integrated forcing over the atmospheric lifetime of the particles to determine the change in energy balance resulting from each packet of emissions. This integrated forcing corresponds to the numerator in figure 1.

5.2. Conclusions despite uncertainty

Three-dimensional models are more accurate than this simple two-box model, assuming that their chemistry and physics are
Table 2. Inputs to simple two-box model. BC = black carbon; OM = organic matter; Gf = growth factor (wet diameter at 85% relative humidity divided by dry diameter).

| Transformation rates                           | Units | Central value | 1 − σ | Source, comments       |
|-----------------------------------------------|-------|---------------|-------|------------------------|
| Overall lifetime                              | hours | 171           | 56    | Textor et al 2006 (AEROCOM) |
| Lifetime in surface box compared to overall lifetime | hours | −24           | 18    | Sensitivity tests (NCAR-CAM) |
| BC coating                                    | hours | 14            | 6     | Estimate based on urban observations |
| Fraction aloft                                 |       | 0.2           | 0.15  | Textor et al 2006       |
| Optical properties                            |       |               |       |                        |
| BC absorption                                 | m²/g  | 7.5           | 2.4   | Bond and Bergstrom (2006) |
| BC scattering                                 | m²/g  | 2.5           | 0.5   | Bond and Bergstrom (2006) |
| BC backscatter fraction                       |       | 0.18          | 0.05  | Schnaiter et al (2003)  |
| OM absorption                                 | m²/g  | 0.7           | 0.55  | Sun et al (2007)        |
| OM scattering                                 | m²/g  | 4.2           | 1.5   | Bates et al (2006)      |
| OM backscatter fraction                       |       | 0.12          | 0.03  | Bates et al (2006)      |
| OM hygroscopic growth                         |       | 1.2           | 0.3   | Bond et al 2006         |
| Absorption enhancement by mixing              |       | 1.5           | 0.5   | Bond et al 2006         |

Emission rates (BC, OM)

| Diesel, modern                                | g/kg  | 0.6, 0.25      | 50%  | Bond et al 2004         |
| Diesel, superemitter                          | g/kg  | 6.8, 3.6       | 100% | Bond et al 2004         |
| Biofuel, traditional stove                    | g/kg  | 0.7, 1.7       | 150% | Bond et al 2004         |
| Residential coal                              | g/kg  | 0.2, 0.02      | 500% | Bond et al 2004         |

a Uncertainty increased to allow for parameter uncertainty.
b Hygroscopic growth for backscatter, which is lower than that for total scattering.

Figure 6. Integrated forcing by aerosols emitted from burning 1 kg of fuel; results from 250 Monte Carlo simulations for each of three major sources. Note the scale difference. A few high points are excluded from diesel superemitter and traditional biofuel so the remaining distribution can be better seen. Zero is marked with a thick black vertical line to indicate the fraction of simulations that produce cooling or warming. Dashed lines mark quartiles.

correct. However, the simpler model can be used in Monte Carlo simulations to examine the effect of uncertainties. Each model parameter was sampled from a normal distribution, except for the emission factor which was sampled from a lognormal distribution. These simulations address the question ‘what is the uncertainty in the climate benefit that would result from various actions?’. I examine this question for three of the major sources that appear in figure 1. Thus, it is quite certain that carbonaceous aerosol forcing is a substantial fraction of CO₂ forcing for these sources. For biofuel emissions, aerosol forcing is greater than 20-year CO₂ forcing in 50% of the runs, and greater than 100-year CO₂ forcing in 15%. Aerosols emitted from modern diesel have more forcing than CO₂ over 20 years in 10% of the cases, while superemitter emissions are greater than 20-year CO₂ forcing 90% of the time. Aerosol forcing exceeds 25% of the 100-year CO₂ forcing in 20%, 90% and 55% of the cases for modern diesels, superemitting diesels and biofuel for cooking, respectively. Despite the uncertainty, that fraction is large enough that ignoring it would be short-sighted.

5.3. What missing knowledge is important?

Forcing by carbon dioxide from 1 kg of the same fuel, integrated over 20 and 100 years, is shown on each panel. Thus, it is quite certain that carbonaceous aerosol forcing is a substantial fraction of CO₂ forcing for these sources. For biofuel emissions, aerosol forcing is greater than 20-year CO₂ forcing in 50% of the runs, and greater than 100-year CO₂ forcing in 15%. Aerosols emitted from modern diesel have more forcing than CO₂ over 20 years in 10% of the cases, while superemitter emissions are greater than 20-year CO₂ forcing 90% of the time. Aerosol forcing exceeds 25% of the 100-year CO₂ forcing in 20%, 90% and 55% of the cases for modern diesels, superemitting diesels and biofuel for cooking, respectively. Despite the uncertainty, that fraction is large enough that ignoring it would be short-sighted.

Placing a value on the climatic effects of individual actions is one effort that could be hampered by the amount of uncertainty. An organization that supports actions to reduce climatic impact...
may be uncomfortable with such large uncertainty in the net benefit, and hence in the benefit-to-cost ratio.

Much of the uncertainty in figure 6 is caused by lack of knowledge about emission totals and black carbon fractions. High emission factors, allowed by the lognormal random sampling, cause much of the high tail in each figure. When the simulations were re-run without variability in emission quantities and properties, the coefficient of variation (standard deviation divided by the mean) was reduced from above 100% to 40–50%.

Of the model variability not attributable to emission uncertainties, about 60% of the squared variation is due to lifetime and 40% is due to normalized forcing. Aerosol vertical location in addition to optical properties affects the latter. Thus, a large fraction of the uncertainty in forcing results from aerosol transport and removal processes, which should receive at least as much study as aerosol optical properties.

Two important physical processes are not included in the two-box model. The first is the role of aerosol in brightening clouds (the ‘indirect’ effect). Hansen et al (2007) suggest that this cooling reduces warming by carbonaceous aerosols, but does not eliminate it. The second effect is changes in snow albedo through deposition of absorbing aerosol. Flanner et al (2007) estimated that this snow forcing could increase forcing by 10–30%. Regional variability in transport and removal and surface albedo is not included here, either. These factors could be addressed in future work. Nonlinearities due to interactions between different aerosol species (Stier et al 2006) could also be incorporated.

6. Conclusion

Aerosols have acknowledged effects on climate, and reductions could contribute to mitigating those effects, especially for near-term climate change. However, aerosol forcing is ignored when evaluating actions and when making decisions about promising actions. Although warming aerosols are part of the global scientific picture, they are not yet considered in conventional portfolios for action to reduce climatic impact. Here, I have examined four barriers to such considerations:

(1) Will carbon particles soon be addressed by local regulations? Not completely. Local regulations are unlikely to address some major emitting sectors, and may not address important, high-emitting fractions of the other major emitting sectors.

(2) Do carbon particles have primarily local effects? No, their regional forcing is much greater than their local forcing.

(3) Are aerosols too complex to address when quantifying net benefits of actions? No, aerosol physics is indeed complex, but scientists can and already do distill knowledge to simple metrics.

(4) Are climatic effects of black carbon too uncertain to quantify actions? While there is substantial uncertainty, aerosols emitted from diesel engines and biofuel for cooking warm climate with a very high probability, and contribute a substantial fraction of the total forcing from these sources.

Because of the uncertainties, more work remains for aerosol scientists. Emission characterization can reduce uncertainty in total forcing from individual actions to levels that may be acceptable, about 50%. Additional confidence requires a better understanding of atmospheric transport and removal processes as well as aerosol optics. Despite the uncertainties, some of the major objections to considering aerosols under hemispheric or global agreements are illusory, and vanish when examined closely.

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