Current and Future Climate Effects of Black Carbon

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This talk discussed the possible effects on climate of controlling emissions of particulate black carbon. The talk was divided into two segments, one focusing on the effect of the mixing state of black carbon on its direct radiative forcing and the second on the global- and regional-scale climate response of controlling fossil-fuel black carbon plus organic matter emissions. Work on the mixing state and direct forcing is summarized in References 1 and 2. Work on the climate response is summarized in Reference 3. Figures shown in the talk are provided in the references, which are accessible via the internet links provided. Below is a summary of each of the two segments.

The mixing state and resulting direct forcing of black carbon

Particulate black carbon (BC) warms the air primarily by absorbing solar radiation. The extent of absorption is affected by whether BC is coated by other material, such as organic matter, sulfate, or sea spray. When BC is coated, sunlight that would otherwise pass by the particle is refracted into the particle, enhancing absorption. As such, the coating of a BC particle enhances its radiative heating.

In Reference 1, the effect of three optical treatments of BC on global direct radiative forcing were examined. In the first, BC was treated as externally mixed (separate) from all other particle components. In the second, BC was treated as well-mixed internally with all other particle components (its refractive index was volume averaged with that of other components). In the third, BC was treated as a core in an internal mixture, surrounded by a shell of other components. It was found that the external-mixture treatment resulted in the least absorption, giving the least positive radiative forcing of BC. The well-mixed internal mixture resulted in the most absorption (the most positive radiative forcing). The core treatment gave results halfway between the other two treatments. It was argued that the well-mixed treatment is unphysical, since BC is a solid and cannot be diluted throughout particles; thus, in reality, BC forcing should lie between the externally-mixed treatment and core treatments.

The next issue that arose was the mixing state of BC in the global atmosphere. Relative to the volume of the atmosphere, an infinitesimally small number of measurements of the mixing state of BC have been taken. Whereas many measurements, primarily those away from BC emission sources, show that BC is internally mixed to some degree, others, primarily those near such sources, show that BC is externally mixed (please See References 1 and 2 for a discussion of measurements of BC mixtures. Because measurements are so few and far between, the only way currently to estimate the global-scale mixing state of BC is through numerical modeling in conjunction with measurements.

To that end, a study of the evolution of the global-scale mixing state and direct forcing of BC was performed (Reference 2). During the study, a global model treated the evolution of 18 size distributions. The 18 distributions consisted of four "primary" distributions (sea spray, soil, black carbon, and organic matter) into which emissions occurred, one "primary" distribution (sulfate) into which homogeneous nucleation occurred, two additional BC distributions into which primary BC grew, 10 "binary" distributions that resulted from heterocoagulation among simpler distributions, and a completely-mixed distribution that resulted from all higher heterocoagulation interactions. The primary distributions and sulfate were initialized, and the aerosol population was relaxed with continuous emissions into the primary distributions, homogeneous nucleation of the sulfate distribution, and coagulation, growth, chemistry, transport, deposition, and rainout among all distributions until a near global-scale steady state was obtained.

In the end, it was found that the mixing state and direct forcing of BC approached those of an internal, not an external, mixture. The resulting direct forcing exceeded 0.5 W/m^2. If correct, this suggests that BC may be the second-leading cause of global warming in terms of direct forcing after carbon dioxide and ahead of methane.

The climate response of controlling emissions of fossil-fuel BC+OM

The next issue that arose was the effect of controlling emissions of black carbon on climate. In Reference 3, simulations analyzing the effect of BC controls from fossil-fuel sources were carried out. Since organic matter (OM) is emitted along with BC during combustion processes producing BC, the simulations included the effects of simultaneous BC and OM reductions. Results of the study were as follows:

A) Control of fossil-fuel (f.f.) particulate BC+OM emissions may be the most effective method of slowing global warming in terms of the speed and magnitude of a cooling per unit mass emissions reduction. The Kyoto Protocol of 1997 did not contemplate controlling BC+OM; this conclusion and the associated analysis suggest quantitatively that such controls would be beneficial.

B) Any mass emission reduction of f.f. particulate BC+OM may slow warming more than any emission reduction of CO_2 or CH_4 for a specific period. When all f.f. BC+OM and anthropogenic CO_2 and CH_4 emissions are eliminated together, that period may be 25-100 years.

C) Diesel cars emitting continuously under the most recent U.S. and E.U. particulate standards (0.08 g/mi; 0.05 g/km) may warm climate per distance driven over the next 100+ years more than equivalent gasoline cars; thus, fuel- and carbon-tax laws that favor diesel at these standards appear to promote global warming.

D) Toughening passenger vehicle particulate emission standards by a factor of eight (0.01 g/mi; 0.006 g/km; e.g., the California 2004 Low Emission Vehicle II standards) does not change this conclusion, although it shortens the period over which diesel cars warm to 13-54 years. (Note that these results assume that all vehicles emit at the standards and does not consider vehicles that may have technologies resulting in lower emissions or older vehicles without emission controls).

E) Historical net global warming can be attributed roughly to greenhouse-gas plus f.f. BC+OM warming minus cooling due to other particulates. The net observed warming (about 0.7 K since the mid 1800s) is estimated to be due to the difference between total warming (+1.9 K) and total cooling (1.2 K). Since f.f. BC+OM causes about +0.35 K of

the total warming, its elimination would reduce more than 40% (+0.35/+0.7) of net warming (>15% of total warming) to date.

F) There are at least 12 identifiable feedbacks of aerosol particles to climate, including the self-feedback effect, photochemistry effect, smudge-pot effect, daytime stability effect, effect of BC absorption on the first indirect effect, BC-low-cloud positive feedback loop, rainout effect, BC-water-vapor positive feedback, indirect effect, semidirect effect, particle effect through surface albedo, and particle feedback through large-scale meteorology.

G) Reducing BC+OM will not only slow global warming but also improve human health. This conclusion was paraphrased by U.S. President George Bush. On May 18, 2001, the President obtained a draft copy of Reference 3 and this statement. In a speech on June 11, 2001, the President stated, "Reducing both (black soot and tropospheric ozone) would not only address climate change, but also dramatically improve people's health."

References

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(3) Jacobson M. Z. (2002) Control of fossil-fuel particulate black carbon plus organic matter, possibly the most effective method of slowing global warming, *J. Geophys. Res., 107*, in press, http://www.stanford.edu/group/efmh/fossil/fossil.html