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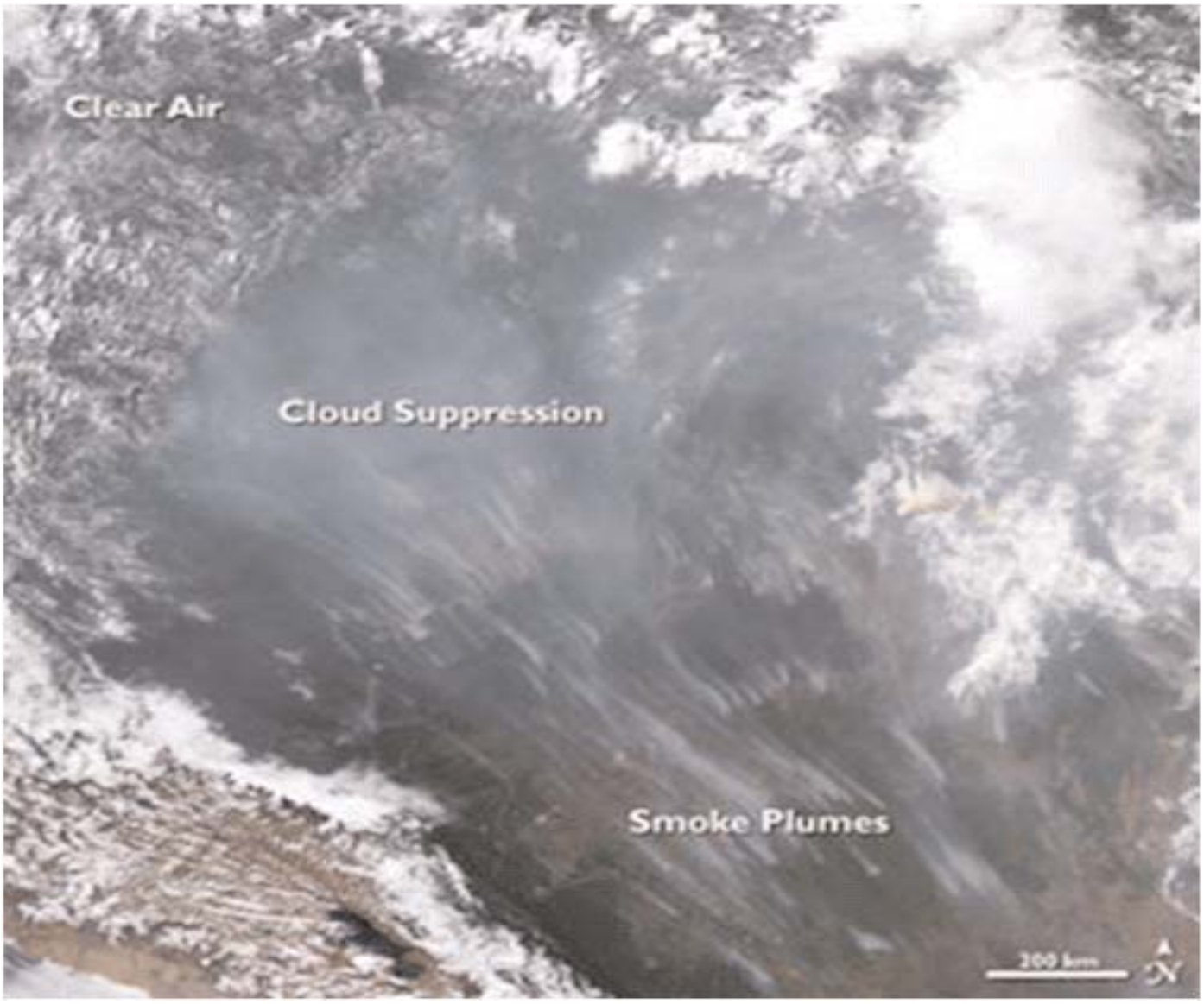
BLACK CARBON:
A Science/Policy Primer

JOHN BACHMANN I VISION AIR CONSULTING, LLC I DECEMBER 2009



Cover Image: NASA image of smoke plumes from biomass burning in western Brazil and Boliva in September 2005. Absorption of sunlight by the dense soot and smoke suppresses cloud formation in this event. In other circumstances, air pollution particles can have the opposite effect of 'seeding' and increasing the number of cloud droplets. Both effects can reduce the amount of rainfall in areas of higher concentrations (Kaufman and Koren, 2006).

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2101 Wilson Blvd
Suite 550
Arlington, VA 22201

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Abstract

Over the last decade, a growing body of evidence indicates that soot and smoke from incomplete combustion are major contributors to climate change. Black carbon, a soot component, is a potent climate driver that absorbs sunlight in the atmosphere, changes rainfall patterns, and when deposited on snow and ice, accelerates melting. In addition, soot can cause direct effects on health and agriculture. Climate and other effects of soot are magnified in broad regions where the strongest source emissions occur, but transported soot is also a major concern in the Arctic. The short atmospheric lifetime of soot particles also means that emissions reductions produce nearly immediate results, in contrast to most greenhouse gases (GHGs).

The principal source categories include diesel engines, small industrial sources, residential coal and solid biofuels for heating and cooking, and open biomass burning for agriculture and forestry. Control and mitigation approaches exist, but the small size and wide dispersion of these sources present significant challenges. The available evidence suggests that appropriately targeted soot controls have the potential to accelerate and enhance climate and air quality related public health benefits when used as a complement to overall climate strategies centered on greenhouse gases. Consideration of such controls is, however, subject to a number of scientific and technical uncertainties and complexities regarding emissions, controls, and the net effect of addressing some soot sources on both global and regional scales. This paper summarizes current knowledge on the effects of soot components—black carbon and organic particles—on climate, and identifies sources and technologies to mitigate their impacts. It also presents perspectives on the potential role of soot mitigation approaches in developing more comprehensive climate strategies.

Introduction

Authoritative scientific panels state unequivocally that the earth is warming (IPCC, 2007; Bierbaum et al., 2007). Climate change is happening, it is caused in large part by human activity, and it will have many serious and potentially damaging effects in the decades ahead (IPCC, 2007). As a result, world leaders have met repeatedly in recent years to forge agreements on goals and strategies to address the issue. In the United States, the Congress has drafted climate legislation and a number of states have emerging climate programs. Most development and analyses of climate strategies have focused on reducing emissions of

carbon dioxide (CO_2) and other greenhouse gases (GHGs), which are widely recognized as the major contributors to current and projected climate change.

In recent years, however, growing evidence has implicated the oldest recognized form of air pollution—soot and smoke from incomplete combustion—as a significant but unique contributor to climate change. Several studies have suggested that black carbon, a component of soot, may be the second or third most important climate driver behind CO_2 on a global scale, and might even be more important in certain regions (Jacobson, 2000; Hansen et al., 2000; Ramanathan and Carmichael, 2008; Shindell and Faluvegi, 2009). Some have also noted that, unlike the case for CO_2, soot reductions produce nearly immediate results because soot is removed from the atmosphere within weeks (Jacobson, 2002). In addition, soot emissions can cause direct effects on health and may affect precipitation patterns on a local and regional scale. The available evidence suggests that appropriately targeted soot controls have the potential to accelerate and enhance both climate and air quality related public health benefits as a complement to overall GHG-based climate strategies (Jacobson, 2007; Hansen et al., 2000; Wallack and Ramanathan, 2009; Grieshop et al., 2009). Consideration of such controls is, however, affected by a number of important scientific and technical uncertainties and complexities regarding emissions, controls, and the net effect of addressing some soot sources on both global and regional scales.

This white paper provides an overview of the state of scientific and technical knowledge on the effects of soot and its major components—black carbon and organic particles—on climate and on technologies to mitigate its impacts. The purpose is to highlight aspects of that information useful in evaluating the potential role of alternative strategies to reduce soot emissions as a component of developing more comprehensive climate policies. It is intended as an introduction to the issues and uncertainties for policy-makers, business leaders, and environmental professionals.

Soot Science

Fundamentals: sources, properties and interactions

Most of the energy produced for power, industry, transportation, and domestic purposes is derived from combustion of various carbon-containing fuels like coal, oil and gas (fossil fuels), or wood and ethanol (broadly called biofuels). Complete combustion of these fuels produces CO_2, the most important GHG, as well as water vapor and a number of pollutants such as nitrogen oxides, sulfur oxides, and trace elements that depend on the specific fuel. These air pollutants play a lesser, but still significant, role in climate change compared to CO_2. In practice, however, all combustion is subject to varying degrees of inefficiencies that result in the production of additional pollutants—soot and smoke, including particles consisting of mixtures of black (mostly elemental) carbon solids, hydrocarbons and other organic

compounds[1] in solid and liquid form, as well as organic vapors and carbon monoxide (CO).

Soot is a mix of amorphous microscopic particles that contain black carbon, organic carbon, and smaller amounts of sulfur and other chemicals. Dense soot from diesel combustion usually appears black because it contains a high fraction of so-called black carbon, which absorbs all colors of light (see Figure 1). Smoke plumes from open biomass burning may appear brown, blue, or gray because their less efficient combustion produces a much higher fraction of organic carbon particles relative to black carbon. Organic carbon particles from incomplete biomass combustion not only scatter light, but can also partially absorb certain wavelengths, resulting in a brown coloration of the smoke particle material (Jacobson, 2007).

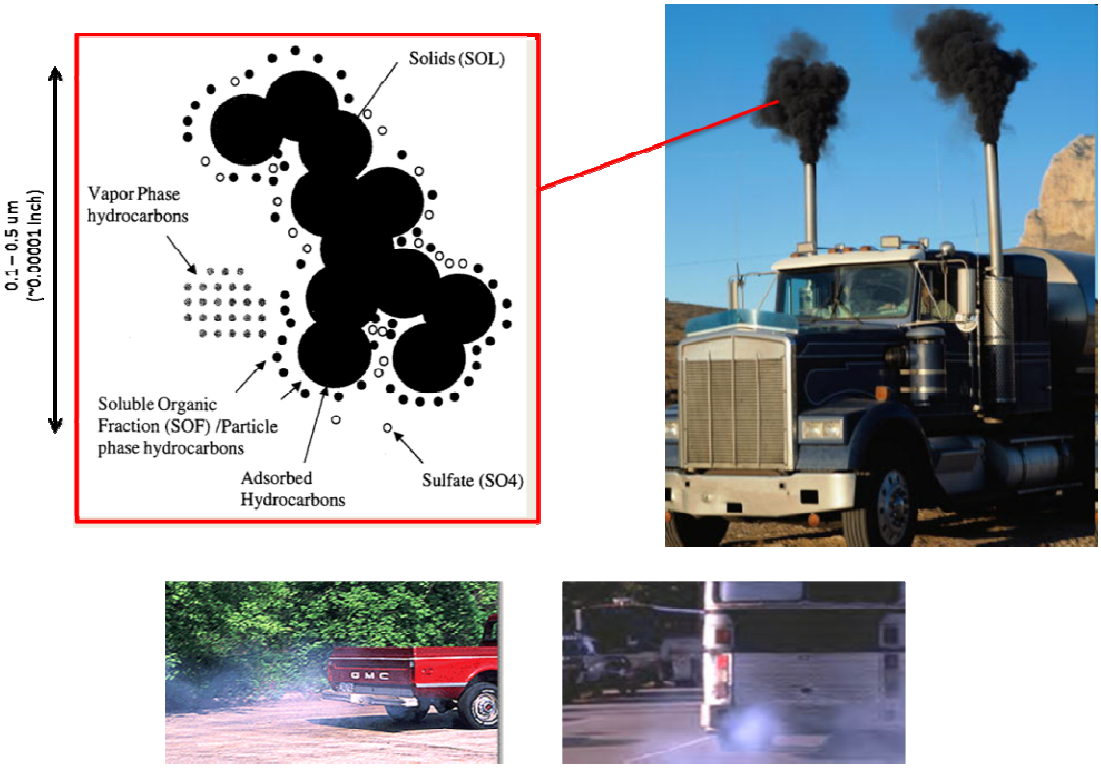


Figure 1. A close look at soot. *Freshly emitted diesel soot includes aggregates of very small black carbon particles together with condensed organic compounds and sulfates. Black carbon absorbs all wavelengths of light, causing dense emissions to appear black. Small soot particles also scatter light, resulting in bluish to white plumes. The particles continue to mix in the atmosphere, increasing the effective light absorption.*

[1] "Organic" compounds contain carbon chemically combined with other elements, usually hydrogen (as in hydrocarbons), as well as oxygen (e.g., alcohols), nitrogen, and others. CO_2 is classified as an "inorganic" compound. The products of incomplete combustion of both fossil fuels and biofuels include black carbon particles and complex mixtures of hydrocarbons and other organics with multiple carbon atoms in each molecule (e.g., polycyclic aromatic hydrocarbons).

Soot particles heat the air by absorbing sunlight, warming the atmosphere by emitting that energy through heat (infrared) radiation and conduction to the air around them. This differs from GHGs like CO_2, which allow sunlight to pass through, but absorb the Earth's heat radiation and reemit it to the air (see Figure 2). Soot is therefore far more effective at absorbing energy than CO_2.[2] When soot particles age in the atmosphere, they become coated by relatively transparent or translucent chemicals, increasing their size and the probability that sunlight will hit them and be absorbed by the particles. These "aged" coated soot particles heat the air more than do newly emitted, uncoated soot particles (Jacobson, 2007; Bond, 2007a.)

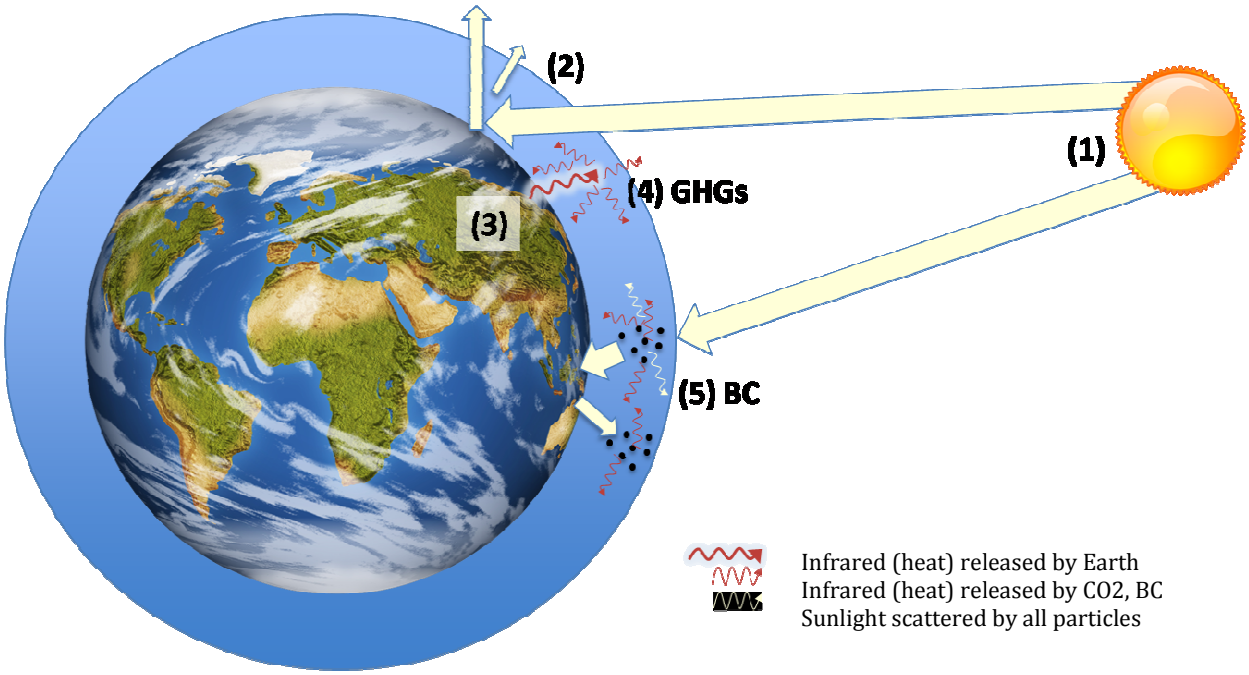


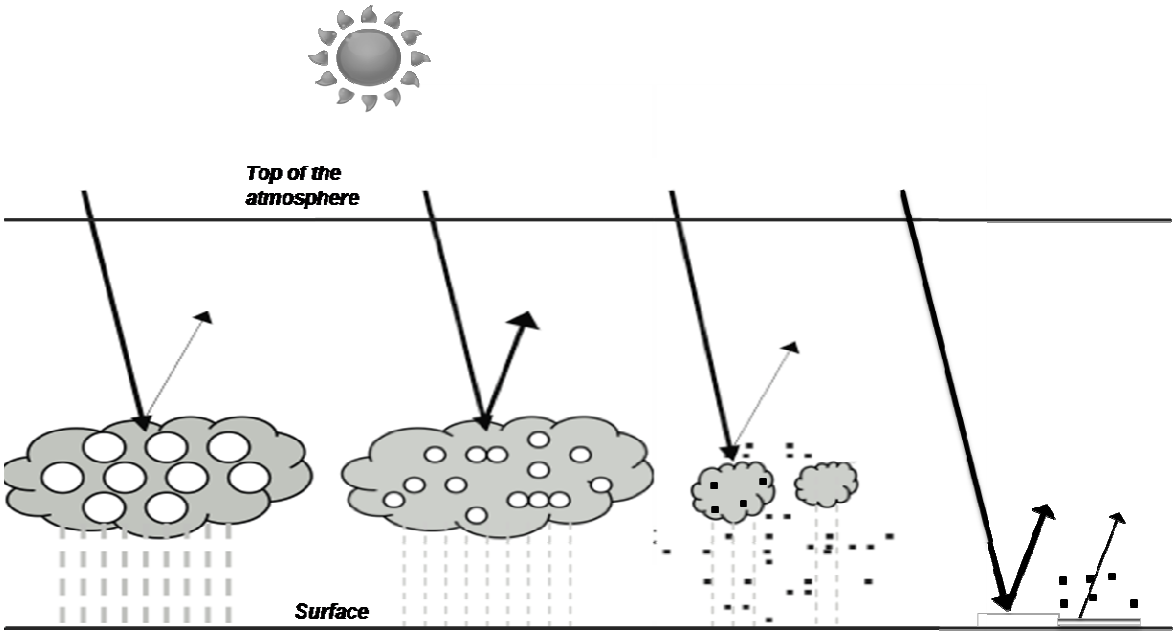
Figure 2. How greenhouse gases and black carbon particles in the atmosphere alter Earth's energy balance*. About half of the incoming solar radiation (1) is absorbed by earth's surface, warming it, about a fifth is absorbed by the atmosphere, and the rest is reflected (2) by the earth's surface, atmosphere, and clouds. The warmed surface radiates heat (infrared radiation) outward (3). Most of the infrared radiation from the surface is absorbed by greenhouse gases (GHG) and clouds and is then reemitted, warming the lower atmosphere and earth's surface (4). In contrast, black carbon particles in soot absorb both incoming and reflected sunlight (5) and heat the atmosphere. The picture is more complex because the overall mix of particles (sulfates, organics, and black carbon) also scatters incoming sunlight, reducing the amount reaching the surface (cooling). Black carbon and other particles also influence climate indirectly by various interactions with clouds and snow and ice (see Figure 3).*

[2] On a mass basis, these properties mean that an ounce of black carbon particles can absorb over a million times more radiant energy than an ounce of CO_2 (Jacobson, 2009). Because CO_2 emissions are more than 3000 times higher and its atmospheric lifetime is over 2500 times longer than black carbon, CO_2 is the dominant driver of global warming.

The warming caused by GHGs and black carbon is partially offset by light scattering from other particles produced by combustion, such as organics, sulfates (from sulfur dioxide), and nitrates (from nitrogen oxides). Incoming sunlight scattered by these particles in all directions reduces the amount of sunlight that reaches Earth's surface, resulting in cooling. The amount of black carbon relative to other particles is a critical factor in assessing the impact of combustion sources on climate. In general, sources with higher black carbon (warming) to organic carbon (cooling) ratios are more likely to result in a net warming. The major sources of soot ranked in order of black carbon to organic carbon particle content are fossil fuels, solid biofuels (wood, agricultural and animal waste), and biomass burning (fires set for agriculture and forestry and wildfires) (Bond, 2007). The warming and cooling caused by absorption and scattering of sunlight by airborne particles described above are considered to be "direct" effects (Forester et al., 2007).

Black carbon and other combustion particles also operate through several "indirect" mechanisms that may cool or warm the atmosphere as well as redistribute rain and snowfall (Figure 3). Several of these indirect mechanisms occur through interactions with clouds. As illustrated in Figure 3b, all combustion particles may increase the reflectivity of clouds. This results in cooling by reducing the amount of sunlight reaching the ground, but also may change rainfall patterns. These effects are greater for water-soluble particles like sulfates than for less soluble substances found in soot, such as black carbon and many types of organic particles. Soot particles are unique, however, in that 1) they can hasten cloud evaporation, allowing more sunlight to reach the Earth's surface (Figure 3c); and 2) soot materials can continue to warm even after they are removed from the atmosphere when they fall on snow and ice (Figure 3d). By darkening the surface, soot warms and changes the character of the snow, which hastens melting, particularly in the spring. Where such early melting uncovers darker surfaces beneath (e.g., rock or ocean water), the net effect is magnified because these surfaces themselves absorb much more sunlight.

One of the most important differences between CO_2 and soot is how long each remains in the atmosphere. The effective atmospheric lifetime of CO_2 emissions is over a century. As a result, CO_2 and other long-lived GHGs are relatively evenly distributed around the globe, reducing some of the uncertainties in estimating their effects. This persistence also means that it would take some time to realize the benefits of a reduction in CO_2 emissions. By contrast, soot and other combustion particles can persist in the atmosphere only for days to a week before they are removed by rain, snow, or 'dry' fallout. Even though they can travel hundreds to thousands of miles from source regions in this time, soot and other particles tend to be found in highest concentrations over regions of high industry, populations, and emissions. Concentrations are much lower over oceans and landmasses distant from source regions. This means that soot effects on temperature, visibility, and rainfall can be considerably stronger in and near source regions. The short lifespan of soot also means that such effects will be diminished very quickly following emissions reductions.



a) Unpolluted cloud has larger droplet sizes as only natural particles are available to form them.

b) By acting as seeds (condensation nuclei) small particle pollution can increase the number and decrease the size of cloud droplets. This increases the 'reflectivity' of the cloud and prolongs its life (increasing cooling) but may also decrease rainfall

c) Soot particles in cloud droplets increase light absorption. Release of absorbed radiation may cause clouds to shrink (increase warming) and decrease rainfall.

d) Soot particles deposited on snow or ice absorb sunlight and increase melting, exposing darker surfaces beneath that continue to absorb even more sunlight.

Figure 3. Indirect particle effects. *Schematic diagram showing several "indirect" mechanisms by which particle pollution, including black carbon, may influence temperature and precipitation through cloud modifications and deposition to snow and ice (modified from Forester et al., 2007). The open circles represent cloud droplets while the black dots are soot particles. Straight lines represent the incident and reflected sunlight; larger or smaller width indicates how much light is reflected. The vertical grey dashes represent rainfall. White and grey rectangles (d) represent clean and soiled snow-covered ground, respectively.*

Quantitative Comparisons of Warming by GHGs and Black Carbon

Considerable scientific effort has gone into determining how much black carbon and CO_2 and other GHGs have contributed to current estimates of global warming. This involves accounting for the balance of global energy flows in far more detail than shown in Figure 2, addressing the countervailing direct and indirect effects outlined in Figures 2 and 3, and incorporating the distribution as well as the specific physical and chemical characteristics of the various gases and particles involved.

While no single universally accepted metric has emerged that captures all of the critical factors, many researchers have used "radiative forcing" (RF). RF is an estimate of the change in the balance of incoming sunlight and outgoing heat caused by a pollutant (e.g., mechanisms shown in Figure 2) or other climate driver. As reported by the Intergovernmental Panel on Climate Change (IPCC) and many others, the estimate represents the global average of the difference between present day and the beginning of the industrial era as measured in watts per square meter (W/m^2) (Forster et al., 2007).[3] The RF value is useful in comparing the global average warming associated with various pollutants and other climate drivers.[4]

The IPCC (Forester et al., 2007) has estimated a combined net forcing of all human-related pollutants of 1.6 W/m^2 with a range of 0.6 to 2.4 W/m^2 that reflects the uncertainty. On this basis, they concluded that it is "*extremely likely* that humans have exerted a substantial warming effect on climate" (IPCC, 2007). The net forcing is composed of both positive (warming) and negative (cooling) components. The largest positive contribution is by long-lived GHGs[5] at 2.63 [$\pm$0.26] W/m^2. The small uncertainty is indicative of a "high level of scientific understanding" (Forester et al., 2007). Ozone and other GHG effects add 0.37 W/m^2 for a total GHG forcing of 3 W/m^2. GHG forcing is partially "masked" by the net cooling from light scattering by particle pollution of -0.5 [$\pm$0.4] W/m^2, and an estimate of indirect particle forcing (by increased reflectivity of clouds) of -0.7 with a range of -1.8 to +0.3 W/m^2. Note, however, that the IPPC judged the particle scattering estimate to be supported by a "medium to low" scientific understanding and assigned a low level of scientific understanding to the indirect estimate.

Figure 4 compares IPCC radiative forcing estimates for several specific GHGs and classes of particles, including black carbon. The results suggest that black carbon forcing is important even on the scale of GHG forcing. Nevertheless, significant uncertainties remain in both of the two forcing estimates shown for black carbon. Modeled black carbon forcing estimates can differ for a variety of reasons, including the strength and categories of included emission sources, treatment of the "aging" of particles, the predicted vertical distribution of black carbon, and whether the estimate is "constrained" by inclusion of real world observations (Ramanathan and Carmichael, 2008).

Most of the modeling used to generate the lower estimate for black carbon in Figure 4 did not adjust for the 60 to 100 percent increase in absorption that occurs as soot particles mix and "age" in the atmosphere and also did not adjust for differences between the predicted absorption and actual measurements (Koch et al., 2009). Field measurements of particle

[3] A watt per square meter (W/m^2), equivalent to two mini Christmas light bulbs on a card table, may not seem like much and is small compared to incoming solar radiation. Given earth's surface area, however, 1 W/m^2 amounts to 510 trillion watts, or over 30 times larger than the annual worldwide consumption of energy.

[4] As discussed in subsequent sections, this is only one definition of RF; RFs can also be compared for different geographic regions and for several vertical layers of the atmosphere.

[5] Long-lived GHGs include CO_2, methane (CH_4), nitrous oxide (N_2O), halocarbons, and sulfur hexafluoride (SF_6).

absorption from a worldwide network (AERONET) are reported to be twice or more larger than "unconstrained" model predictions (Sato, 2003; Schuster et al., 2005).[6] A model evaluation study using more comprehensive measurements found that model estimates of total black carbon absorption were biased low, varying by region. In Asia, for example, the models underestimated absorption by 40 percent (Koch et al., 2009). The higher direct black carbon forcing in Figure 4 is derived from a study that adjusted for aging and integrated AERONET, satellite, and other observations into the modeling. Other estimates based on observations have found both smaller and larger direct forcing for black carbon (Ramanathan and Carmichael, 2008).

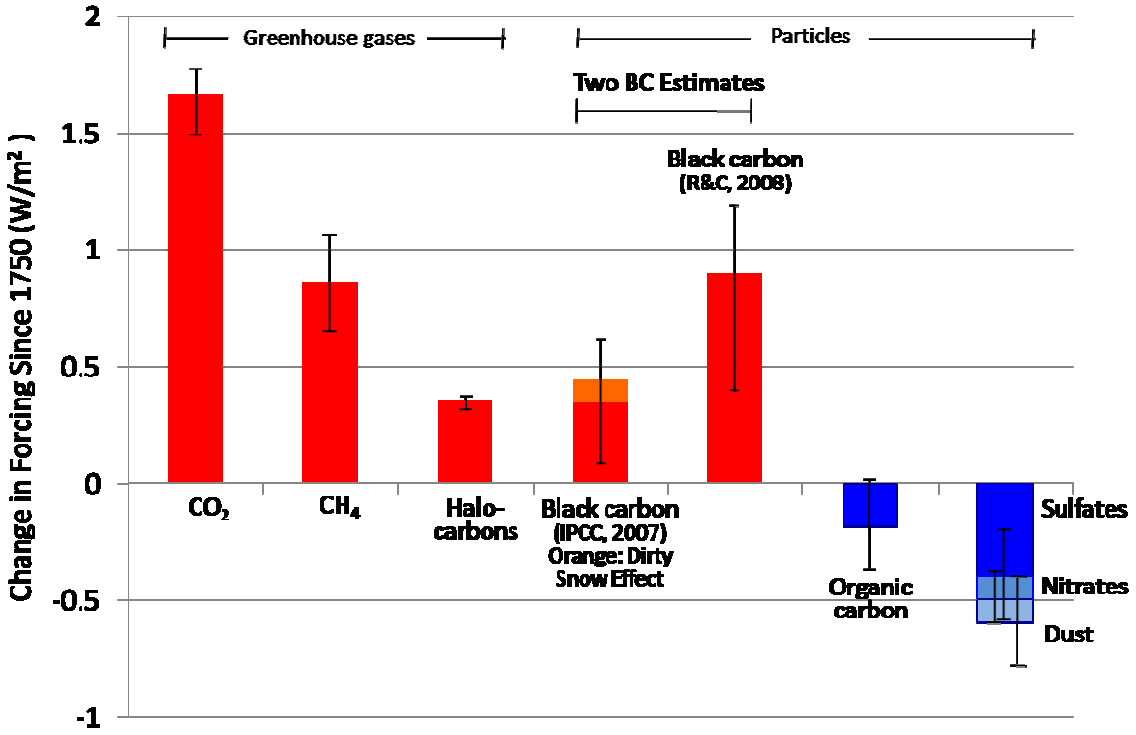


Figure 4. Radiative forcing and associated uncertainty estimates for several major GHG and particle components *(Forester et al., 2007, except Ramanathan and Carmichael 2008 for second black carbon estimate). Note that two estimates for black carbon are shown. Red (warming) and blue (cooling) bars show direct positive and negative (absorption vs scattering) forcing respectively. Black carbon also warms by snow darkening (orange) and cloud effects (not included). Black carbon may be the second or third most significant warming pollutant. The net forcing of black carbon sources is, however, reduced by cooling from co-emitted organic carbon (shown) and its contribution of increased cloud reflectivity (not estimated).*

[6] A large part of the discrepancy appears to be attributable to the lack of adjustment for mixing/aging in the models.

Comparisons of globally averaged forcing for GHGs and particles do not account for the substantial differences in their geographic and atmospheric distribution. As noted above, black carbon levels are much higher near source regions, resulting in an uneven distribution of forcing across the globe compared to long-lived GHGs. The vertical distribution of forcing is also different. CO_2 causes a positive forcing both in the atmosphere and at the surface. Absorption of sunlight by soot has the countervailing effects of heating the atmosphere and cooling the surface (Figure 2). On a global average basis, Ramanathan and Carmichael (2008) estimate that black carbon alone produces an atmospheric forcing of +2.6 W/m^2 and a surface forcing of -1.7 W/m^2. The combined forcing for both layers (+0.9 W/m^2) is that shown in Figure 4.

Because sources of soot also are responsible for a significant fraction of organic carbon, uncertainties in the net forcing for black carbon (positive) and associated organic particles (negative) are particularly important. This net forcing can vary significantly with the reflectivity of the underlying surface (e.g., white ice or clouds vs. dark sea). When soot particles are present over a darker surface, the incoming sunlight absorbed by black carbon and scattered toward space by the organic carbon reduce the sunlight reaching the surface (dimming). This cooling effect partly offsets the atmospheric heating caused by black carbon. However, when these particles exist over white clouds or a snow covered surface, the energy balance is changed. Much of the reduction in sunlight reaching the ground caused by absorption and scattering by soot would have been reflected upwards by the white surface anyway; this greatly diminishes the potential cooling. At the same time, the increase in reflected light from white clouds or snow enhances the total absorbed by soot. This 'white cloud' effect adds to uncertainties of atmospheric forcing estimates because of the difficulties inherent in modeling the extent and altitude of clouds and the vertical distribution of the particles.

Additional uncertainties in net forcing by black carbon sources are related to the nature and quantity of organic carbon material emitted and formed in the atmosphere. Directly emitted organics tend to be less efficient at scattering light than sulfates and other water-soluble particles. As the mix ages, the solubility and related scattering may increase somewhat. As noted above, some organic particle materials, particularly some emitted by biomass and biofuel burning or formed by atmospheric reactions, can also absorb light (Kirchstetter et al., 2004; Andrae and Geleneser, 2006; Magi, 2009). Because few models have incorporated this effect, direct forcing estimates for organics may overestimate the extent of cooling. Uncertainties in both the absolute and relative emission strengths of black carbon and organic carbon emissions form a large component of the uncertainty in respective forcing estimates (Bond, 2007).

In addition to radiative forcing, other metrics have been used to compare relative impacts of pollutants in climate studies. One, the global or regional average change in temperature, is roughly related to forcing. It includes the effect of additional interactions and feedbacks. Accordingly, it requires more complex simulations to calculate. Another, the global warming potential (GWP), attempts to address the wide disparity in the atmospheric lifetimes of

various pollutants. Lifetimes for the pollutants in Figure 4 range from about 100 years (CO_2) to 10 years (methane) to weeks (particles and ozone). GWP is defined as the total forcing attributed to a mass of emitted pollutant during a specified time after emissions (typically 100 years) as compared to the same mass of CO_2. Although black carbon is a far more potent warming agent per unit mass, its effects disappear within one to two weeks after emissions stop. Because CO_2 remains in the atmosphere for over 100 years, the total forcing over time continues to increase long after emissions stop.

While useful for evaluating the degree of warming, none of these measures can be used to compare the contribution of these agents to the overall climate response caused by them, which involves changes in weather patterns, cloud cover, rainfall and more. The following section discusses modeling results that include some quantitative estimates of forcing and temperature change for black carbon as well as, in some cases, effects on other aspects of climate. Comparisons of emissions reductions based on GWP are taken up in sections on sources and control implications.

Geographic and Atmospheric Distribution of Black Carbon and Other Particle Effects

Figure 5 illustrates the geographic distribution of black carbon emissions and associated atmospheric warming as well as the location of surface cooling from black carbon and other particles. Unlike long-lived GHGs, which have only moderate variation in forcing with latitude, the strength of particle forcing varies significantly with location. Black carbon forcing can be over ten times higher in and near global regions of greatest source strength, particularly regional hotspots located in the tropics and East Asia. This is due to the one to two week lifetime of atmospheric particles, which limits the extent to which they can be transported and mixed far from source regions. Still, transport of black carbon is sufficient to contribute significantly to effects as far away as the Arctic. Figure 5 also highlights the vertical split of black carbon forcing between atmospheric heating (5b) and surface cooling (5c). Light scattering by all particle types provides additional cooling shown at the surface.

Climate Effects in Regions of High Black Carbon Emissions

The nature of soot and the geographical distribution of sources mean that black carbon can have powerful direct and indirect regional effects on climate beyond those caused by GHGs. Over the past several years, a number of studies have begun to examine the multiple linkages by which black carbon, in combination with other particles and GHGs, may be affecting regional climate, including temperature, rain and snowfall patterns, water supply, and available sunlight. Many of these studies have focused on Asia, which has the world's highest black carbon emissions (Bond et al., 2004).

One of the first such studies examined a shift in rainfall patterns in China, one of the areas of most intense particle pollution (Figure 5). In recent decades, China has experienced increased

heavy rains and flooding in the South and increased drought and dust storms in the North. Climate model simulations of contributing factors found that the combined effect of atmospheric heating by black carbon and surface cooling by all particles resulted in rising air and more clouds and rain in the South and a related increase in sinking and drying air in the North (Menon et al., 2002). Subsequent modeling supported a black carbon influence on drying in the North, but raised the possibility that natural variability may have been responsible for the increases in the South (Meehl, 2008).

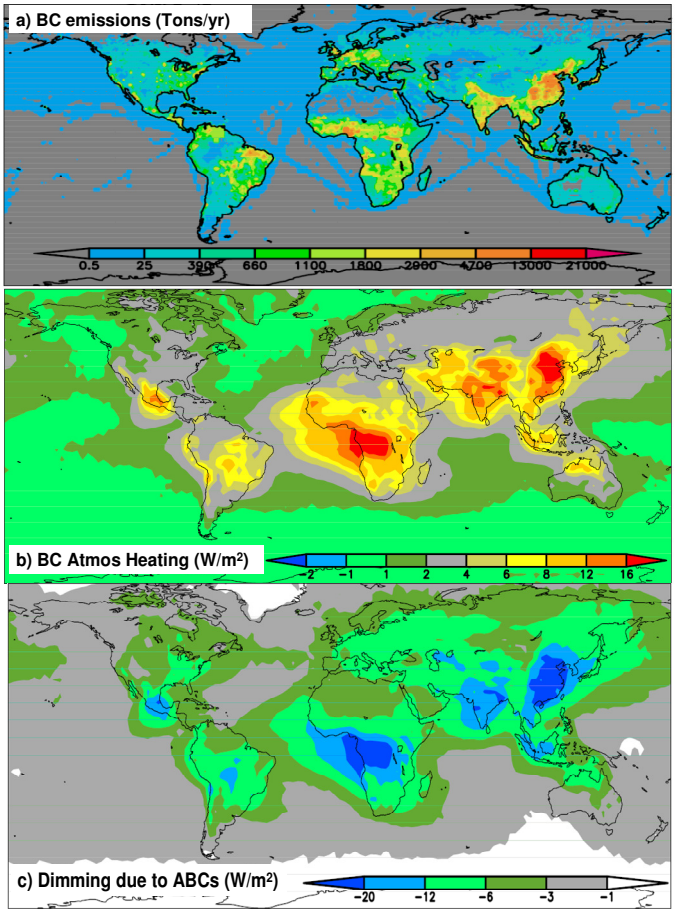


Figure 5. Global distribution of black carbon sources and radiative forcing *(Carmichael and Ramanathan, 2008). a) The strength of black carbon emissions. b) Atmospheric heating due to black carbon absorption of solar radiation. c) Reduction in solar radiation at the surface (dimming) by all combustion particles (black carbon and others) in the atmosphere. Unlike GHGs, black carbon concentrations and forcing are unevenly distributed, with the largest values concentrated in and downwind of the strongest source regions.*

Several studies have examined the influence of GHGs and persistent high particle pollution on the observed weakening of the Indian monsoon (Figure 6). The monsoon is critical for

agriculture and water supply across the region. Early climate modeling suggested that if GHGs were acting alone, the monsoon season rainfall should have been increasing (Meehl et al., 2000). Subsequent studies have offered mechanisms, supported by modeling, to show how atmospheric warming and surface dimming by particles could account for this weakening. These involve a number of factors including reduced gradients in sea surface temperatures, reduced seawater evaporation from dimming, decreased land-sea contrast in surface temperature, and increased atmospheric temperatures (Ramanathan and Carmichael, 2008; Ramanathan et al., 2008).

Recent work with climate models that couple ocean and atmosphere interactions have found that black carbon atmospheric absorption and particle "dimming" at the surface result in modest increases in pre-monsoon rainfall during the spring and a decrease in summer monsoon rainfall in India, both in agreement with observed trends (Meehl et al., 2008; Lau and Kim, 2006). These results generally support a strong role for black carbon in weakening the Indian monsoon and shifting precipitation patterns in Asia. Given the complexity and uncertainties in the systems, however, it is important to continue both modeling and field work to improve our understanding of the role of cloud-particle interactions, natural variability, emissions, and other factors.

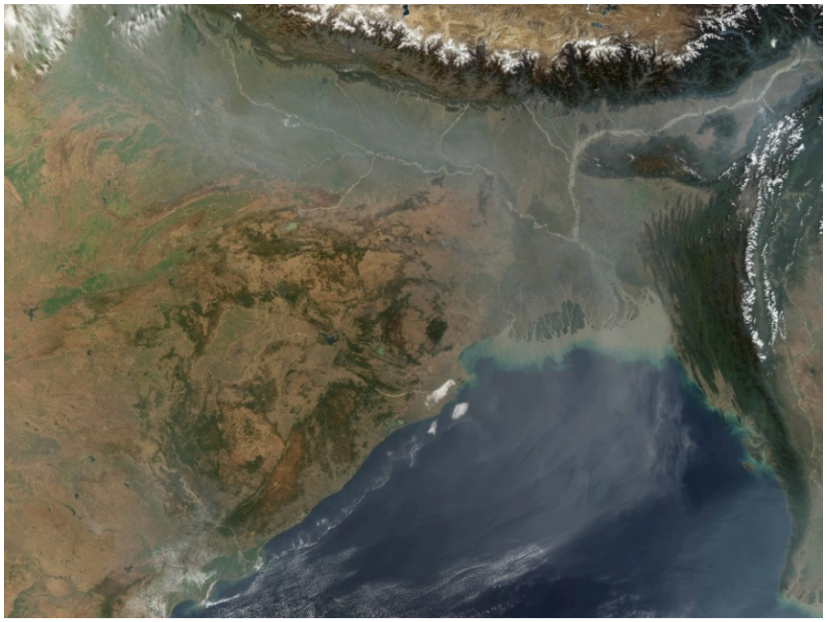


Figure 6. Haze over the Ganges Delta*. Against the Himalaya Mountains (top of image), "rivers" of particle pollution flow through Northern India and Bangladesh to the Bay of Bengal on February 1, 2006. Haze in this region comes from combustion of biofuels for home cooking and heating, fossil fuels for transport and energy, and crop lands for agriculture burning (biomass). The grayish appearance of the haze from space indicates it is both absorbing and scattering sunlight. Credit: MODIS image from NASA's Terra satellite:* http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=16027&oldid=13341.

Reduced precipitation from the Indian monsoon may contribute to the accelerating retreat of the Himalayan Glaciers (Figure 7). The glacier-fed rivers originating from the mountain ranges surrounding the greater Tibetan Plateau influence the lives of about 40 percent of the world's population (Zemp and Haeberli, 2007). Observed atmospheric warming, primarily from GHGs, has been suggested as the major factor in melting of these and a large fraction of glaciers worldwide (IPCC, 2007). Recent assessments, however, suggest a major contribution from soot (Ramanathan et al., 2008). Climate simulations suggest that atmospheric heating by black carbon in South and East Asia warms air in the Himalayas by up to about 0.6 °C, which is comparable to temperature increases estimated for GHGs (Ramanathan and Carmichael, 2008). The simulations predict this warming produces a 10 to 20 percent reduction in springtime snow depth on the Tibetan plateau (Meehl et al., 2008). These estimates do not, however, account for cooling by organic particles in soot or cloud interactions.

Figure 7. Himalayan Glacier Retreat*. Gangotri, the source of the Ganges River, has been retreating since 1780, but at a faster pace after 1971. Evidence suggests global warming from GHGs and regional increases of black carbon are contributing significantly to this phenomenon in the Himalayas (Ramanathan and Carmichael, 2008; Ming et al., 2008). The IPCC notes that the Himalayan glaciers, the source of water for billions of people in the region, are retreating faster than in any other part of the world. (Cruz et al., 2007). Credit: NASA EROS Data Center, September 9, 2001:* http://www.gsfc.nasa.gov/topstory/20020530glaciers.html.

The above simulations also do not include the warming effect of soot deposition to the Himalayan Glaciers. This deposition darkens the snow and ice, increasing sunlight absorption (Figure 3d), and "primes" snow for earlier melt by changing its surface characteristics (Flanner et al., 2007). Flanner et al. (2007) coupled a global climate model with one that simulates the behavior and radiative characteristics of black carbon particles deposited on snow and ice. As the authors note, modeling of these factors is subject to a number of uncertainties, and there are few relevant field data by which to test them. The results suggest an annual forcing associated with soot darkening over the Himalayan glacier region that ranges as high as 3.8 W/m^2 or more, with a springtime peak of over 20 W/m^2. The critical Tibetan plateau had the highest degree of soot-related snow forcing in the world, followed by

the area in Northern and Eastern China where very high regional loadings of soot and significant snowfall intersect.

Forcing from snow darkening is amplified in the springtime because large expanses remain covered by snow while the intensity of sunlight is increasing. To the extent that darkening hastens the spring snowmelt, warming is enhanced by the longer period where more absorptive land surfaces are exposed to the sun. A follow-up simulation study found that in the spring, even organic particles, which are darker than snow covered surfaces, increase net heating (Flanner et al., 2009). The authors observed that their simulations "suggest that fossil fuel and biofuel emissions of [black carbon and organic matter] induce 95 percent as much springtime snow cover loss over Eurasia as anthropogenic carbon dioxide" based on a "strong" snow darkening effect and the large black carbon emissions in Asia (Flanner et al., 2009).

Atmospheric heating and dimming by soot from high levels of biomass burning and other particles also may be contributing to observed reductions in precipitation in Africa. Rostayn and Loman (2002) suggested that the link between dimming, the north–south gradient in sea-surface temperatures and a decrease in land rainfall contributed to the Sahel drought of the 1970s and 1980s. Huang et al. (2009) found a large-scale connection between smoke and dust particles and reduced precipitation in the West African Monsoon. Based on comparison with climate modeling, these authors found that the observed suppression of light to moderate rainfall were consistent with a major contribution of radiative forcing by black carbon.

Black Carbon Contribution to Arctic Warming

Recent evidence suggests that black carbon may also have a disproportionate influence on climate in a region with generally low emissions and concentrations—the Arctic. In this case, it is the character of the snow and ice covered region that serves to enhance the net strength and effectiveness of black carbon and related organic particle forcing.

Arctic temperatures have risen at twice the average global rate over the past 100 years (IPCC, 2007). This warming has been accompanied by an earlier onset of spring ice melt, a lengthening of the melt season, and increasing discharge from the Greenland ice sheet. The total area covered by summer sea ice decreased by 40 percent between 1979 and 2007, resulting in the first recorded complete opening of the Northwest Passage (Quinn et al., 2007). While natural variability may explain some of the recent changes in sea ice extent, the overall trend toward warming and melting has been attributed primarily to human-induced climate change (Min et al., 2008; Holland et al., 2008). Recent modeling predicts complete disappearance of summer arctic sea ice by 2040 (Perovich and Richter-Menge, 2009).

The impacts of ice loss include an important amplifying climate feedback—the reduction of the extent to which Earth's surface reflects the Sun's radiation. As warming causes greater

amounts of snow to melt, bare sea ice and eventually dark ocean water are exposed, which absorb more radiation. This positive feedback leads to further warming and is one of the reasons that the Arctic is highly sensitive to global warming. The earlier onset of Arctic spring melt observed in recent years is of particular concern, as this is the season of maximum feedback due to snow and ice melting (Hall and Qu, 2006). It is also the season of maximum estimated forcing by soot (Quinn et al., 2008). This warming and melting has significant consequences for the land, ice, and aquatic ecosystems in the Arctic. It also has implications beyond the Arctic, as melting of Arctic land-based glaciers is one of the factors contributing to global sea-level rise (Quinn et al., 2007).

The large extent of ice and snow and the positive feedback increase the relative importance of forcing from snow darkening in the Arctic. Because of the positive feedback described above, "Black carbon on snow warms the planet about three times more than an equal forcing of CO_2" (Hansen and Nazarenko, 2004). Flanner et al. (2007) found inclusion of black carbon in snow for simulations reflecting 1998 and 2001 produced a global averaged warming of 0.15°C and 0.10°C, respectively; the snow darkening had a much greater impact in the Arctic, where annual temperature increases were estimated at 1.61°C and 0.50°C for the two years in this study. Simulations by Shindell et al. (2009) estimated the total contribution of transported black carbon to Arctic warming since 1890, including atmospheric and snow forcing, at about 0.5°C to 1.4°C.

The results of climate modeling indicate a significant contribution by black carbon to Arctic warming. Quantitative estimates of forcing and temperature change are, however, particularly uncertain in this region. In addition to the various issues and uncertainties inherent in climate modeling noted in the sections above, airborne and deposited black carbon comes mainly from distant source regions, the more uncertain forcing from snow darkening and modification appear to dominate the total, and atmospheric and snow measurements of black carbon and associated organics are limited in the region. The net direction of forcing from soot transported from a range of sources, particularly in the Spring, is less in doubt because negative forcing from light scattering particles is reduced with a highly reflective surface beneath, and even organic particles may cause warming (Quinn et al., 2008; Flanner et al., 2009).

Health and Agricultural Effects in Areas of High Black Carbon emissions

The high level of soot particles illustrated in Figure 5 also presents substantial risks to public health and agriculture in these regions. As a significant fraction of particle pollution, soot emissions are strongly associated with a variety of direct health effects. About three billion people are exposed to elevated particle pollutant levels in the "hot spot" regions, but exposures to these pollutants in most urbanized regions of the world also present significant risks to health. In the last 15 years, thousands of published studies have collectively revealed a convincing relationship between particle pollution and serious health effects, including premature death in people with heart or lung disease, aggravation of respiratory and

cardiovascular disease (as indicated by increased hospital admissions and emergency room visits), impaired lung function and increased respiratory symptoms, as well as evidence of changes in heart rhythm (EPA, 2004; 2006a). People with heart or lung diseases, the elderly, and children are at greatest risk of these effects. In general, these studies do not find convincing evidence of any specific "threshold" below which the risk is zero.

The greatest concern is for smaller "fine" particles, which includes almost all combustion-related particles such as black carbon and associated organic compounds. While most epidemiologic studies have used a measure of fine particles to index pollution, a number have implicated various components within the mix of fine particles, notably sulfates, nitrates, carbon, organic compounds and metals (EPA, 2005; 2006a). The consensus of the EPA and its external science advisors has been that "many different components of fine particles and a variety of different source categories are all associated with, and probably contribute to, effects associated with [fine particles]" (EPA, 2006a). Accordingly, the United States, as well as many other countries and the World Health Organization (WHO), have adopted standards and guidelines that regulate fine particles as a group. Accordingly, these countries are taking action to reduce all fine particles. Because large combustion sources are generally well controlled for soot, particle and acid rain control programs are driving major reductions in sulfur dioxide emissions; while this reduces health risk and direct environmental effects, it also decreases the contribution of sulfates to cooling.

Some health-effects studies have examined important source categories of black carbon, most notably diesel emissions and biofuel and biomass burning. By definition, such studies encompass exposures to all of the products of incomplete (and complete) combustion near the source. Several such studies have found that mortality and illness increased the closer residences were to roadways or measures of truck traffic (EPA, 2006). A recent study in the Netherlands found significant associations between mortality and a measure of "black smoke," which in urban areas is a marker for diesel emissions (Brunkreef et al., 2009). Recent reviews summarizing studies of outdoor exposures to wood and other solid biofuels as well as large scale biomass burning found associations consistent with more general studies of particulate matter (Boman et al., 2006; Naeher et al., 2007). In the case of biofuel cooking and heating, however, the highest exposures often occur indoors. A growing number of studies provide evidence of significant effects of these indoor exposures, particularly in children and women (Smith et al., 2004; Naeher et al., 2007).

WHO (Cohen et al., 2004) developed estimates for the global health burden of urban air pollution using particulate matter mortality studies and concentration estimates for cities with populations larger than 100,000. They estimated 800,000 premature deaths annually, with 65 percent of them in Asia. More recent regional studies have used modeling to extend coverage to smaller cities and rural areas as well as more recent concentration-mortality relationships and assumptions. Saikawa et al. (2009) modeled the contributions of Chinese sources of sulfate, black carbon, and organic particles to mortality, estimating 470,000 premature deaths in China alone, and 30,000 more worldwide. Preliminary central mortality estimates for fine particles in the United States ranged between 63,000 and 88,000 annually

(EPA, 2009), compared to 28,000 for North America by the WHO. Anenberg et al. (submitted), who extended a similar modeling approach to global emissions, also estimated much higher totals than the WHO, but with a similarly high proportion in Asia. All of these estimates are subject to substantial uncertainties inherent in the underlying health studies, as well as in all of the component steps and assumptions in the assessment.

It is currently not possible to specify the portion of these particle pollution mortality estimates borne by the sources of soot. All of the particle emissions from soot sources (and some of the gases) can contribute to health effects. Based on the current information, it would not be appropriate to assign a greater or lesser weight to black carbon and related organics beyond their contribution to total fine mass. This contribution varies substantially with location relative to various source categories, but often accounts for about a third or more of total fine mass in urban areas. Absolute levels also vary greatly. In Beijing, for example, annual levels of black carbon and organic particles alone were over twice the level allowed by the U.S. standard for total fine particles, while levels in Southern California were about a third of those in Beijing. (Yang et al., 2005; EPA, 2008)

WHO also developed a risk assessment for the additional burden from indoor exposures related to household use of solid fuels (biofuels and coal) (Smith et al., 2004). The assessments used fuel consumption to estimate exposure and effects from three cooking-related disease endpoints with the strongest data. They found 1.6 million deaths were attributable to indoor smoke from solid fuels, or about 3 percent of the WHO estimates for the total global burden of all disease.

Much less work has been done on the effect of black carbon source emissions on agriculture. Several studies (e.g., Chameides et al., 1999) estimated that the reduction in sunlight from regional "dimming" from soot, sulfate, and other particles in Asia might diminish crop yields by about 10 percent or more. As noted above, however, the combined effects of dimming and heating by particles also may have substantial effects on rainfall and evaporation, which may offset or amplify the reduction in sunlight (UNEP, 2008). One study did examine the combined effect of these factors on the monsoon season rice crop in India and found that both GHGs and black carbon, as well as other particles, may have contributed to the slow down in harvest growth that has been observed since 1985 (Aufhammer et al., 2006).

Black Carbon Emissions Sources and Controls

Overview of Global Black and Organic Carbon Emissions and Sources

The most widely used global emission inventory estimates that about 8 million tons[7] of black carbon and 37 million tons of organic carbon are emitted annually (Bond et al., 2004). The major source contributions for black carbon include 40 percent from coal and oil burned in industrial and mobile sources, 18 percent from residential biofuels for heating and cooking (wood, agricultural and animal waste), and 42 percent from open biomass burning, including intentional burning in agriculture and forestry as well as wildfires (Figure 8a, Table 1). The expected contribution of these source types to warming depends in large part on the ratio of black to organic carbon shown in Figure 8b. In general, sources with higher ratios (e.g., diesels) are more likely to result in positive and larger net forcing (warming) compared to those with lower ratios (e.g., open burning). As noted in Figure 8, however, all of these sources also emit CO_2 and other GHGs (that warm the climate) and sulfates, nitrates, and other particles (that cool the climate). The total effect of a source on forcing is derived from modeling based on a combination of all of these uncertain emissions estimates.

Estimates of black and organic carbon emissions are more uncertain compared to those for CO_2 or sulfur dioxide due to the large number of small, dispersed sources with irregular operating conditions, such as cookstoves, biomass burning, traffic, and construction equipment. Determining the magnitude, and in some cases the direction, of forcing for various sources is therefore subject to significant uncertainties. Based on their analyses of the data and assumptions used to develop the inventory, Bond et al. (2004) judge the precision of total emissions to be within a factor of two. Model evaluations (Koch et al., 2007; 2009) have found they predict black carbon surface concentrations reasonably well, with the exception of a significant under-prediction in Asia. It may be that older inventories do not capture the growth in emissions reflected in the more recent Asian surface measurements. On the other hand, these models generally under predict total absorption by particles, but the extent to which this reflects a bias in the inventory or other aspects of the models is less clear (Koch et al., 2009).

[7] "Tons" in this report refers to metric tons (~2200 lb/metric ton).

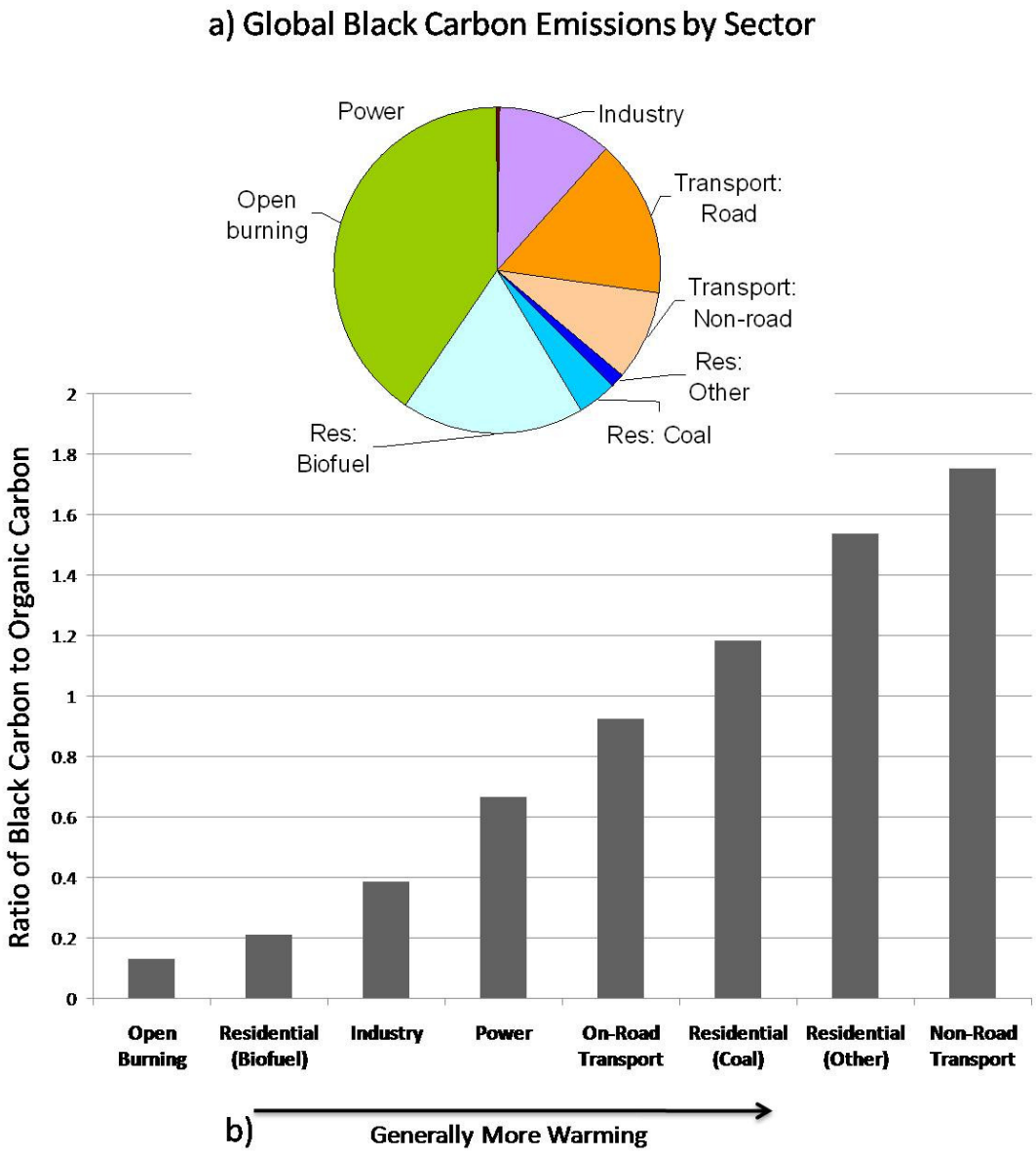
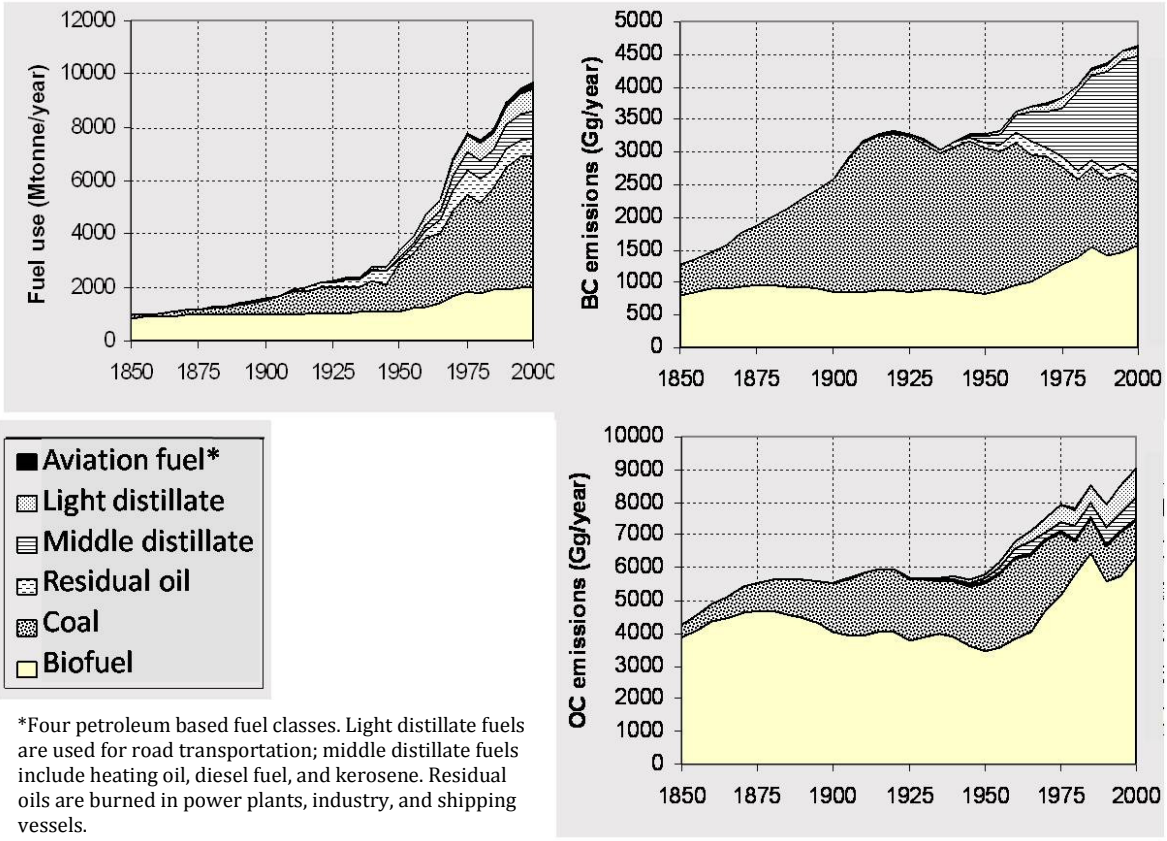


Figure 8. Sources of black carbon and their strengths as warming agents. *a) Global average share of black carbon emissions by sector; the total amount of black carbon emitted globally is about 8 million tons per year. b) The ratio of black carbon to organic carbon for major source categories (Bond, 2004; 2008). Higher ratios indicate generally greater warming, with the important caveat that all of these sources emit significant quantities of other pollutants that may warm or cool the climate, including CO_2 (warming), NOx (ozone and N_2O warming, nitrate cooling). Coal sources also emit significant SO_2 (sulfate cooling), with lesser SO_2 amounts from oil/gasoline, and still less from biofuels. Transportation and biofuel/biomass emissions also lead to ozone and organic carbon that form in the atmosphere downwind.*

Table 1. Global Black Carbon and Organic Carbon Emissions Estimates *(Bond Inventory 7.2.3, based on energy use in 2000). All emissions are in thousand metric tons per year. Total emissions are estimated to be uncertain by a factor of two.*

	BC	OC
Transport		
Diesel on-road	1200	380
Diesel off-road	310	100
Gasoline	92	1000
Marine	120	225
Aviation	22	6
	1700	*1700*
Industry & Power		
Industrial coal	740	1,100
Other	190	990
	930	*2100*
Residential		
Coal	330	280
Wood	1200	5,800
Agricultural waste	260	1,700
Animal waste	37	140
	1800	*7900*
Open Burning		
Crop	330	1,600
Waste	45	59
Other (forest/savanna)	3,000	23,000
	3,400	*25,000*
Other	200	440
Total	8,100	37,000



*Four petroleum based fuel classes. Light distillate fuels are used for road transportation; middle distillate fuels include heating oil, diesel fuel, and kerosene. Residual oils are burned in power plants, industry, and shipping vessels.

Figure 9. Trends in global fuel use and emissions of black and organic carbon, 1850-2000 *(Bond et al., 2007). Driven by a global increase in all fuel use, black and organic carbon emissions from incomplete combustion of fuels have increased since 1850. The relative importance of various fuels has, however, changed dramatically with a substantial reduction in these emissions from coal combustion since 1950, and a marked increase from petroleum-based fuels and biofuels. The reduction from coal is the result of increased combustion efficiency (e.g., from residential to large boilers) and the installation of pollution control devices to remove particles in developed nations (Bachmann, 2007). The recent growth in biofuel consumption occurred largely in developing nations.*

Long-term trends in global emissions of black and organic carbon reveal the significant effect of societal shifts, pollution control programs, and population growth (Figure 9). The substantial decrease in coal emissions is notable. As a result of traditional pollution controls, coal combustion in power plants and large industrial sources around the world are a major source of CO_2 but are generally well controlled for soot. Also notable is the substantial increase in diesel (middle distillate) and solid biofuel emissions since 1950. Present day emission patterns (Figure 10) show that these increases were not evenly distributed around the globe.

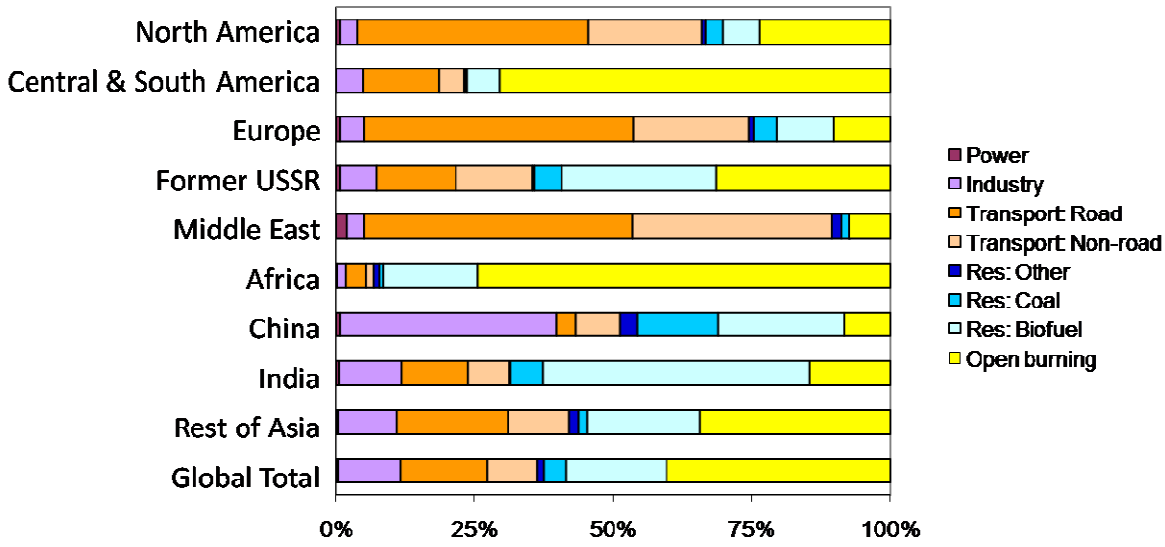


Figure 10. Relative importance of black carbon source categories across regions *(after Bond et al., 2004, updated to 2000 inventory). Open biomass burning (yellow) is the dominant source in Africa and Central and South America. Residential cooking and heating with biofuels (light blue) are large sources in Asia, Africa, and the former Soviet Union. Coal combustion (blue) and transportation (orange) are significant in Asia. In North America and Europe, diesels are the largest source. Asia represents the largest fraction of "contained" (i.e., excluding open burning) global emissions.*

Figure 10 shows that in recent years, open biomass burning and solid biofuels are most significant sources for the sizeable black carbon emissions in Africa, Asia, and South America, while fossil fuels dominate in China, Europe, and North America. A more detailed ranking of source categories for the United States is shown in Figure 11. Figure 5a (above) shows the global geographic distribution of total black carbon emissions. Figure 12 presents the magnitude and source contributions by latitude. The estimates again reflect the split between the dominance of biomass and biofuel vs. fossil fuel combustion in developing and developed countries. As noted in the figure, these patterns have implications for assessing the contribution of source regions to snow melt in the Arctic as well as total soot-related forcing in the Northern Hemisphere.

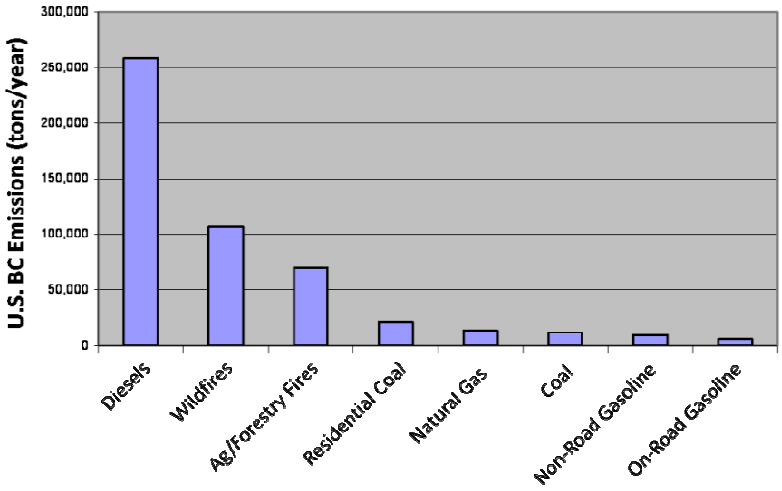


Figure 11. ***Ranking of U.S. sources of black carbon*** *(Sarofim et al., 2009). As in Europe, on- and off-road diesel engine emissions are the largest sources of black carbon in the United States. Recent regulations in both regions require significant reductions in new vehicles. Older vehicles will continue to emit at high levels until they are replaced or modified.*

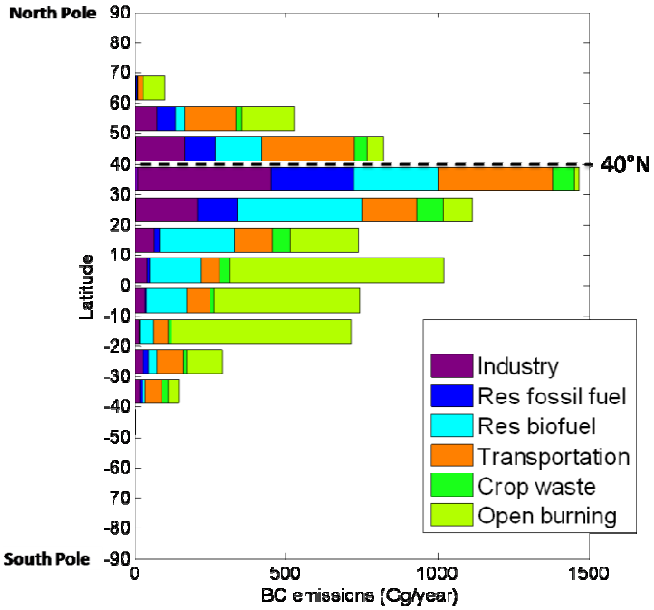


Figure 12. *Geographical distribution of black carbon emissions by latitude (Bond, 2008). Most black carbon emissions, particularly from fossil fuels, occur in the Northern Hemisphere. Black carbon emissions above the 40th parallel (roughly the latitude of New York City and Beijing) are the most likely to increase warming by snow darkening. The potential contribution to Arctic deposition increases the further North the sources are located. See Figure 5a for spatial detail.*

Evaluating Controls for Sources of Black Carbon

Global warming potential: an imperfect metric

This section provides a summary evaluation of potential control approaches for sources of black carbon. As with all such assessments, several questions arise that guide appropriate criteria for evaluations of specific source types. Examples of these include: 1) What techniques are available to reduce or mitigate emissions? 2) What is the extent of potential reductions and applicability of these techniques? 3) How much do they cost? 4) What are the expected benefits and how soon can they be realized? 5) Are there any adverse consequences? 6) How do these factors compare with alternative approaches, including GHG reductions? In considering these factors, it is important to keep in mind that combustion sources of black carbon and GHGs emit multiple pollutants with differing and sometimes opposing effects on climate, e.g., GHGs and black carbon (warming), and sulfur oxides and organic particles (cooling). The total emissions and relative weighting assigned to each of these pollutants is important in determining the overall effect of alternative strategies.

Comparing the magnitude and timing of benefits of black carbon reductions with strategies for GHGs presents some challenges. Estimates of current forcing (Figure 4) are inadequate to this purpose because they do not show how forcing changes over time. This is particularly important for comparing a short-lived pollutant like black carbon with CO_2 or methane. As noted above, a commonly used approach for comparing incremental forcing from pollutant reductions is the Global Warming Potential (GWP). Under the Kyoto Protocol, GWP calculates total forcing of a pollutant "pulse," for example, the release of one ton, over a 100-year period as compared to CO_2. By definition, CO_2 has a GWP of 1. The GWP of methane, for example, is 25, meaning the incremental forcing over 100 years is 25 times that of CO_2. This definition has been criticized for short-lived species, and GWPs have been developed for 20-year and even shorter periods. The choice of time scale, which significantly affects the estimates, is somewhat arbitrary, and based partially on judgments about the weight to give to short-term effects. GWP, like forcing, also fails to capture the significant differences in effects modeled for strong source regions or the Arctic region.

Although GWP is far from perfect as a metric, a number of studies and assessment have used it to provide a rough estimation of the relative cost-effectiveness of different control measures. Analysts continue to work on improved approaches that provide for a more accurate evaluation of short-lived pollutants as well as regional variability (Fuglestvedt et al., 2009; Rypdahl et al., 2009). Table 2 compares estimates of globally averaged GWP and similar metrics for black and organic carbon emissions from several sources. These include both 20-year and 100-year time periods. The relative contribution of black carbon increases when evaluated on a shorter time scale, because all of its impacts occur within the two week lifespan of airborne particles. On average, the positive direct incremental forcing of a unit mass of black carbon is 6 to 10 times greater than the negative value of an equal mass of organic carbon. These estimates do not include potentially significant additional negative forcing from increased cloud reflectivity (Figure 3b), nor the positive effects of snow

darkening (Figure 3d). They also exclude the effect of other pollutants that are emitted from major sources of black and organic carbon. GWPs are used to normalize reductions in pollutants such as black carbon in terms of CO_2 equivalents (CO_2e). Using the Bond and Sun (2005) GWPs in Table 2, a 1-ton reduction in black carbon would be equivalent to a reduction of 2200 tons as CO_2e (20-year GWP) and 680 tons as CO_2e (100-year GWP).

Table 2. Global Warming Potentials (GWPs) for Black Carbon and Organic Carbon Emissions.

Black Carbon		Organic Carbon		Reference
20-year	*100-year*	*20-year*	*100-year*	
2200	680	-250	-75	Bond and Sun (2005)[a]
2530	840-2240	N/A	N/A	Jacobson (2007)[b]
2900	830	-100 to -290	-28 to- 82	Rypdahl et al. (2009)[c]
~2000	~500	N/A	N/A	Hansen et al. (2007)[d]
1600	460	-240	-69	Fuglestvedt et al. (2009)[e]

[a] See also Bond (2007) for details on calculating GWP-like metrics shown.
[b] Estimate for fossil soot, including black carbon, organic carbon and sulfate. Upper bound assumes a shorter CO_2 lifetime.
[c] Ranges for organic carbon reflect different regions.
[d] Uses incremental temperature, estimated emissions from absorption measurements.
[e] Results equivalent to those using IPCC (Forester et al., 2007) models and forcing. Unlike the other studies listed, does not account for particle aging effect.

Table 3 provides an overview of the cost effectiveness of controls for several source categories (Bond and Sun, 2005). As noted, the table is for illustrative purposes. As a point of comparison, analyses of recent U.S. climate legislation estimated CO_2 and related strategies costs at $17 to $22 per ton CO_2e in 2020, rising to $28 to $36 per ton by 2030 (EPA, 2009). Using the 100-year GWP in Table 3 and these CO_2 costs, some diesel retrofit options may not be cost effective based on global average climate considerations alone. As noted above, the 100-year GWP does not credit the faster response of short-lived pollutants; using a shorter time (20 years) increases the relative merit of these controls.

In general, GWP may be of some use for developing relative cost-effectiveness estimates of source emissions reductions, but the metric does not provide a direct measure of the full range of climate related benefits. As discussed above, these may be of particular significance in regions with very high loadings (Figure 5b). Estimates have been developed, however, for health and visibility benefits associated with reductions in particle pollution. Fann et al. (2009) estimated the benefits of reducing carbon-containing particles from mobile sources in U.S. cities at $550,000 per ton, or about 10 times or more than the cost to retrofit diesel trucks.

Table 3. Evaluation of Cost Effectiveness for Eliminating all Black Carbon from Several Technologies *(Bond and Sun, 2005).*[a]

Source	Control Technology	Capital Cost	Cost Effectiveness ($ per ton CO2e)	
			100-year GWP	20-year GWP
Diesel Engines				
Light vehicle	Particle filter	$250-500	25-50	8-16
"Superemitting" light vehicle	Repair, or Vehicle turnover	$500-1000 $thousands	30-130	10-40
Pre-regulation truck	Particle filter	$500-10,000	30-130	10-40
Residential Solid Fuel				
Wood cookstove	Cleaner stoves, fuel switch	$3-100	1-34	0.3-11
Coal cookstove	Cleaner stoves, fuel switch	$3-100	0.2-6	0.1-2
Industry and Power				
Coal: low-tech brick kiln	Switch kiln type (50 percent reduction)		18-35	5.5-11

[a] Illustrative comparison based on numerous assumptions detailed in Bond and Sun (2005) regarding costs, operational lifetime, emissions, and efficiencies. CO_2e based on 100-year and 20-year GWP (see Table 2). Current estimated costs for retrofitting diesels are higher than shown (see below).

The remainder of this section provides a brief summary of information on controls for major source categories of black carbon: transportation, residential cooking and heating, and biomass burning. The discussion does not address certain industrial facilities, including stoker coal oilers, coke ovens, blast furnaces, brick kilns, and oil refinery flaring. Most are primarily smaller and potentially numerous operations in developing countries and the former Soviet Union. More information is needed on the location and contribution of these sources, as well as feasible approaches for controlling them.

Transportation: Diesel Engines

Given their total emissions and high black to organic carbon ratio, it is very likely that diesels are significant contributors to regional and global warming (Bond, 2007). The most effective technology for reducing diesel emissions is the catalyzed diesel particle filter (DPF), which has been proven in millions of vehicles worldwide. The costs and feasibility of installing the DPF varies with age, maintenance condition, size, and operational characteristics. Existing school bus retrofits (smaller engines) have cost about $6000 per vehicle (EPA, 2006b). The most recent estimates indicate that retrofitting heavy-duty trucks with "passive" DPFs are

$11,000-$12,000, and $15,000 for "active" DPF (CARB, 2009). Costs for installation on new vehicles should be substantially lower. Costs for retrofitting non-road vehicles may be similar to those for comparable sized on-road vehicles, but applicability can be limited by the operational and physical characteristics of the wide variety of non-road equipment. This increases the need for custom applications, and reduces the economies of scale. A second widely used technology, the diesel oxidation catalyst, mainly reduces the organic particle fraction, and has little benefit for black carbon (Khair, 2008; Hill, 2009).

Concern over the health effects of particles has led to both tighter ambient air quality standards and increasingly more stringent emission limits for new diesels in the United States, Europe, and other developed nations. As a result, diesel emissions in these countries are decreasing substantially as newer, far cleaner vehicles replace older models. This decrease is expected to continue through about 2030 (Figure 13). Because properly maintained diesel engines have very long life times, however, the opportunity remains for significant reductions though retrofitting existing vehicles. Cost effectiveness varies with the age, expected remaining life, and whether the vehicle has existing but less efficient particle controls.

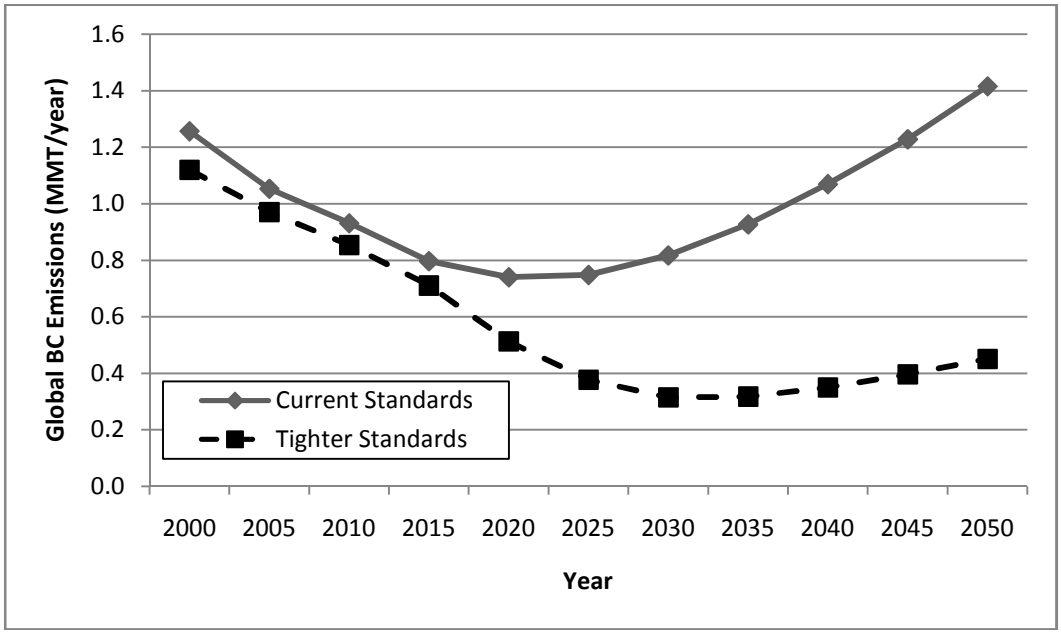


Figure 13. Projected on-road black carbon emissions under current and tighter standards *(after Walsh, 2009b). Current regulations (solid line) result in continued reductions through 2025, followed by increases mostly due to growth in the developing world. Wider application of low sulfur fuels and tighter standards for new vehicles by 2015 in China, India, Brazil, Africa, and the Middle East limits overall global increases (dashed line). Regional breakdown of emissions projections can be found in Walsh (2009b).*

Walsh (2009a) estimates that approximately 54 percent of the 5.4 million heavy-duty on-road vehicles in the United States could be retrofitted with DPFs at a cost of $32 billion. If done in 2010, this would result in a cumulative reduction of 121 million tons of CO_2e (100-year GWP) by 2030. The same analysis suggests about 1.8 million non-road vehicles could be retrofitted at a cost of $27 billion and produce a reduction of 12.8 million tons CO_2e. A preliminary analysis by EPA staff found that 225,000 U.S. diesel vehicles could be retrofitted at a cost of under $50,000 per ton, at a total expenditure of $2.7 billion (Sarofim et al., 2009; Sarofim, 2009). The 66,000 tons of black carbon reduced is about 44 million tons CO_2e at 100-year GWP and 145 million tons CO_2e at 20-year GWP. Cost effectiveness for the latter figure is about $19 per ton CO_2e. Because the estimated CO_2e reductions above use GWP for black carbon without subtracting the effect of organic carbon reductions, these analyses overstate the CO_2e reductions by about 10 percent (Table 2).

A recent analysis examines a proposed program that would mandate retrofits, where feasible, when pre-2007 heavy-duty trucks engines are rebuilt to extend their useful life (Hill, 2009). It is reasonable to expect the per-vehicle costs of retrofits during rebuild to be markedly reduced compared to the estimates above. If instituted in 2010, the program would reduce 96 million tons of CO_2e (20-year GWP). This analysis found the climate benefits of the program would persist for 50 years even assuming DPFs result in a higher than expected 2 percent fuel economy penalty.

After 2025, projected growth in nations without stringent transportation standards increases global black carbon emissions (Figure 13). Diesel particle reduction programs face additional challenges in the developing world. There, low sulfur diesel fuels necessary for DPFs are not yet widely available. Pilot studies have had some notable successes with retrofits,[8] but found some areas where equipment was too poorly maintained to accept lower cost passive DPF, including a number of "superemitting" (poorly tuned) vehicles, some with highly visible smoke plumes (Khair, 2008; CTS, 2006; Subramanian et al., 2009). If wide scale application of retrofits is limited by feasibility and costs, near-term adoption of tighter standards for diesel fuel and new vehicles is the most effective approach. Figure 13 shows the result of a strategy that would begin to address the growth by expanding the availability of low sulfur diesel fuel, followed by the adoptions of tiered standards for new vehicles by 2015 in regions with large projected growth (Walsh, 2009b). Such programs need to pay careful attention to maintaining vehicle performance, as even a small percentage of "superemitting" vehicles can make a large difference in current and forecast emissions (Bond et al., 2004; Bond, 2007; Figure 14).

[8] See list of pilot projects at http://www.epa.gov/international/air/transport.htm#idrp.

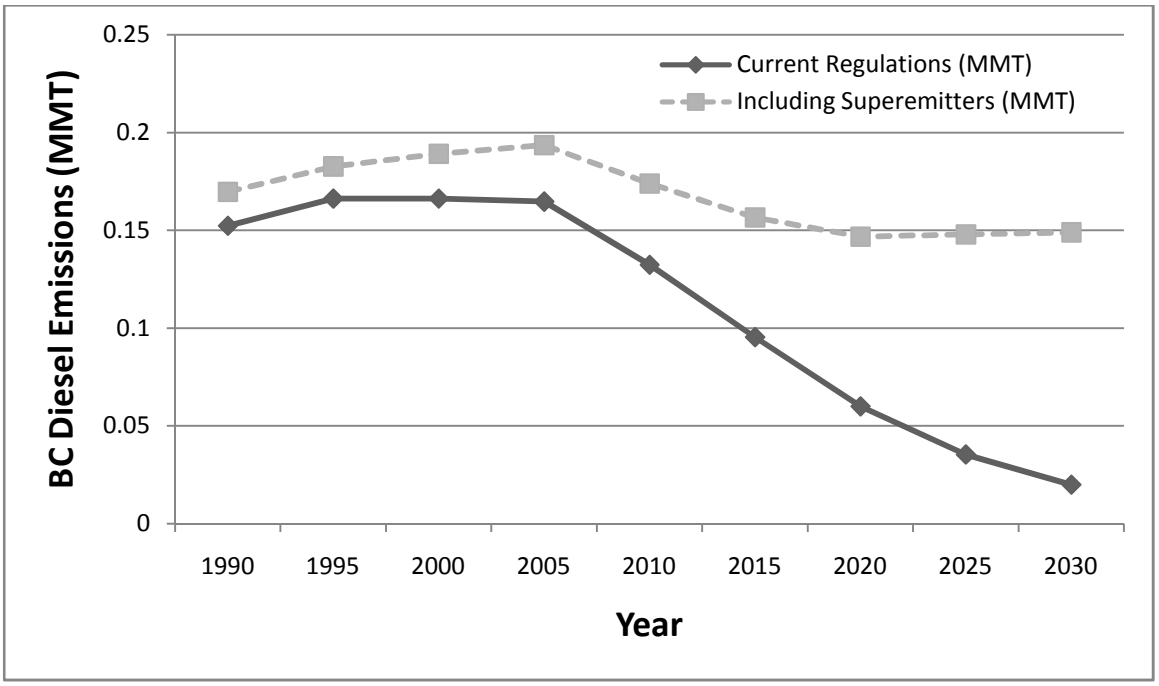


Figure 14. Potential importance of "superemitters" *(after Bond, 2009). Black carbon emissions (in million metric tons, MMT) from light-duty diesel vehicles. Current and projected regulations result in continued black carbon reductions through 2030 (solid line). However, assuming a small fraction of diesel vehicles emit a much higher amount than permitted (poorly tuned "superemitters"), the projected reductions are not achieved. The percentage of superemitters varies, but limited testing in Asia has found it to be as high as 15 percent (Subramanian et al., 2009).*

The forecasts and technologies outlined above do not address alternative approaches, many of which have been advanced to address CO_2 emissions from the transportation sector. Some of these include anti-idling regulations, truck-stop electrification, low carbon fuels, hybrid technologies, and improved rail and other mass transit. Several save enough in fuel use to more than pay for the program and all serve to reduce both CO_2 and black carbon. One approach to reducing CO_2, however, is to increase overall fuel efficiency by switching to diesel passenger cars and trucks. A recent analysis has shown that the net CO_2e benefit of the improved fuel efficiency of diesel vs. gasoline is reduced to only 2 percent when the increased black carbon emissions are considered. A DPF filter increases the net CO_2e benefit to about 17 percent (Walsh, 2009b).

Residential Solid Biofuels

About half of the world's population cooks with solid biofuels (wood, and agricultural and animal wastes) and coal, and projections anticipate the total numbers to continue growing. The marked adverse health effects of particle emissions from these devices provide ample reason for addressing them. As noted above, indoor exposures alone are estimated to be

responsible for 1.6 million premature deaths per year, largely in women and children, who are most exposed (Smith et al., 2004). In addition, a portion of the substantial number of excess deaths per year from outdoor air pollution in Asia, Africa, and South America (Annenberg et al., 2009) comes from cooking and heating. Little doubt exists that, based on commonly used approaches for valuing health improvements, the benefits of reducing these emissions would far exceed the costs (Smith and Haigler, 2008; Fann et al., 2009).

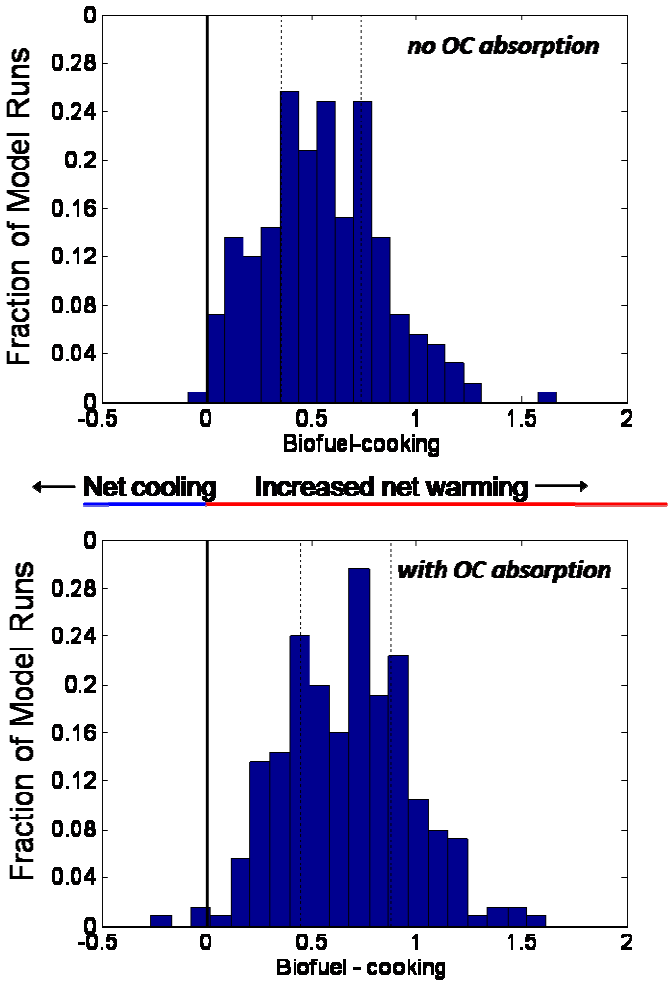


Figure 15. Probability of net forcing from cookstove emissions of black and organic carbon *(Bond, 2008). Integrated net forcing for both black and organic carbon (in gigajoules GJ) emitted from burning 1 kg (2.2lbs) of fuel. Results are based on multiple simulations using a random sampling of distributions that reflect uncertainties in key parameters, e.g. emissions of black and organic carbon (Bond, 2007). Preliminary update includes snow darkening effect and cooling from organic carbon formed in the atmosphere. Including absorption from organic carbon shifts the distribution to the right, resulting in a 98 percent probability that direct forcing for biofuel cooking remains positive. The unknown amount of negative forcing from indirect effects on clouds is an important additional uncertainty for these results.*

Given the higher ratio of cooling organic carbon to black carbon in biofuel emissions (Figure 8), the question for climate strategies is whether reductions from improving stoves or using alternative fuels will also provide net benefits to climate. Figure 15 summarizes an analysis of this issue. These preliminary simulations suggest that the net effect of reductions in black and organic carbon from residential sources are likely to produce a net benefit in terms of direct forcing, subject to a number of limitations and uncertainties.

The most notable issue not addressed in the analysis is the contribution of biofuel particles to increased cloud reflectivity (Figure 3b). While much of the soot particle mix is not water soluble and less effective in this regard, the size of this effect is not known with sufficient certainty. Both the total and relative amounts of organic and black carbon emissions under actual use conditions are also uncertain. Including the indirect effect on cloud reflectivity would raise the chance of a net warming from control. On the other hand, consideration of the other products of incomplete combustion (GHGs and precursors) from cook stoves adds to the weight of evidence that controlling them would produce a net cooling effect (CCSP, 2008), as does accounting for light absorption by some organic particles (Figure 15).

The principal control approaches for wood and other biofuel cooking include basic improved wood stoves, fan stoves, and cleaner fuels (Figure 16). Traditional cook fires and ovens are very inefficient. Basic low cost designs that improve combustion can reduce particle emissions by 50-70 percent; some of these are, however, more effective at reducing organic carbon than black carbon. By contrast, fan stoves can reduce black carbon and other particle emissions by well over 90 percent (Moss, 2009a). Alternative cleaner stoves include gasifiers and solar cookers, although these technologies present additional challenges for domestic users. Clean fuels such as biogas, liquefied petroleum gas (LPG), and methane, can virtually eliminate local particle and other incomplete combustion products, but fossil fuels can increase net CO_2 emissions.

While these technologies are available at reasonable costs (see Table 3), a number of societal, cultural, economic, and infrastructure constraints exist that stand in the way of rapid adoption. The global scale is enormous, including about 500—700 million dispersed low-income households, mainly in Africa, China, India, and South America. A number of efforts are under way, but even at an estimated current rate as high as 4—10 million homes per year,[9] they would reach only 5—20 percent of the market in 10 years. The most notable past success was the large-scale introduction of 129 million improved stoves in rural areas of China between1982 and 1992 (Smith et al., 1993; Zhang and Smith, 2007). Experience in early programs suggests that conditions and financing that must be considered in designing effective transition programs will vary across countries and cultures. Therefore, practical emission reduction solutions in multiple locations may require many narrowly targeted programs (Bluestein et al., 2008).

[9] The Partnership for Clean Indoor Air, which includes many but not all providers of improved stoves, expects its partners to provide clean cooking practices to 2 to 5 million homes in 2009 (Moss, 2009b). If other providers equaled that number, the rate would be 4 to 10 million per year.

Uncontrolled wood - India

Uncontrolled wood - Guatemala

Fan wood stove

Improved basic wood stove

Fan pellet stove

India: household biogas System

Figure 16. Examples of improved cookstoves and fuels. *Top: Uncontrolled wood cooking fires in India and Guatemala. (Photo Nordica MacCarty). Bottom: Available improved stoves and fuels from Phillips, Envirofit/Shell, and Oroja. Fan stoves remove over 90 percent of the smoke while basic improved stoves remove 50- 70 percent. Biogas system processes biomass and burns captured methane, eliminating particle emissions. Not shown: biomass gasifier stoves, and alternative fuels—liquefied petroleum gas (LPG) and natural gas.*

Figure 17 shows the contribution of solid biofuel cooking to Asian loadings of black carbon. Reducing cooking emissions in this 'hotspot' region would appear central to strategies to address the potentially substantial effects of black carbon on regional climate, water supply, and public health summarized above. Based on global simulations that examined a 30 percent reduction in regional emissions for major sectors, Levy et al. (2008) concluded that reductions of biofuel emissions in Asia "appear to offer the greatest potential for substantial, simultaneous improvement in local air quality and reduction of global warming."

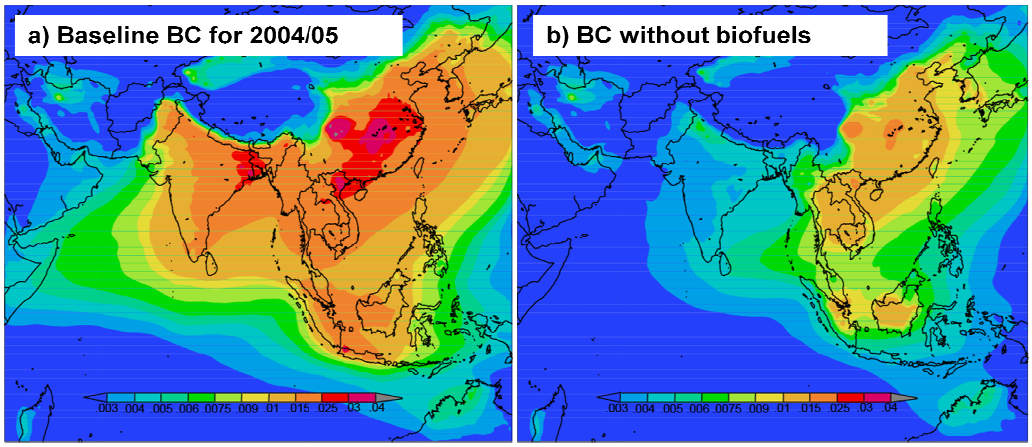


Figure 17. The contribution of biofuel cooking to Asian black carbon loading *(Carmichael and Ramanathan, 2008). a) The simulated annual loading of black carbon particle absorption for 2004–2005. Modeling includes black carbon emissions from biofuel cooking, fossil fuels and biomass burning. b) Same as a, but without biofuel cooking. Atmospheric black carbon loading is indicated in units of optical depth.*

Biomass Burning

Biomass burning includes fires set in evergreen forests, deciduous forests, woodlands, grasslands, and agricultural land, either to clear land for other uses, to stimulate grass growth, or for forest management. A variable but significant fraction is added by natural wildfires (Naik et al., 2007). Biomass-burning particle emissions are more soluble and contain a much lower fraction of black to organic carbon than do fossil fuel soot particles, and a somewhat lower fraction than do biofuel particles. Accordingly, biomass-burning emissions tend to cool climate on a global scale, but may cause regional warming, in part because they also produce ozone, which is a short-lived GHG (Jacobson, 2004; Naik et al., 2007). In situations where biomass burning results in permanent deforestation, however, the warming effect of the added CO_2 emissions exceeds the cooling due to the particles.

In recent years, several developments have increased concerns about the contribution of biomass burning to climate effects. 1) Recent assessments have expanded understanding of the snow darkening effect, particularly in the Arctic, where the cooling effects of organic carbon are diminished by the high reflectance of the surface (e.g., Flanner et al., 2007; 2009). 2) Evidence has grown that organic particles from biomass burning may absorb more light than previously thought. For example, measurements by Magi (2009) suggest that the organic component in African biomass burning particles accounted for about 27 percent of the total particle absorption, with black carbon accounting for the rest. 3) An evaluation study found model predictions of particle absorption in biomass burning regions were 0.4—0.7 of measured values. 4) Modeling and measurements suggest a substantial fraction of black carbon in Arctic snow in the spring may be derived from biomass burning (see Figure 18).

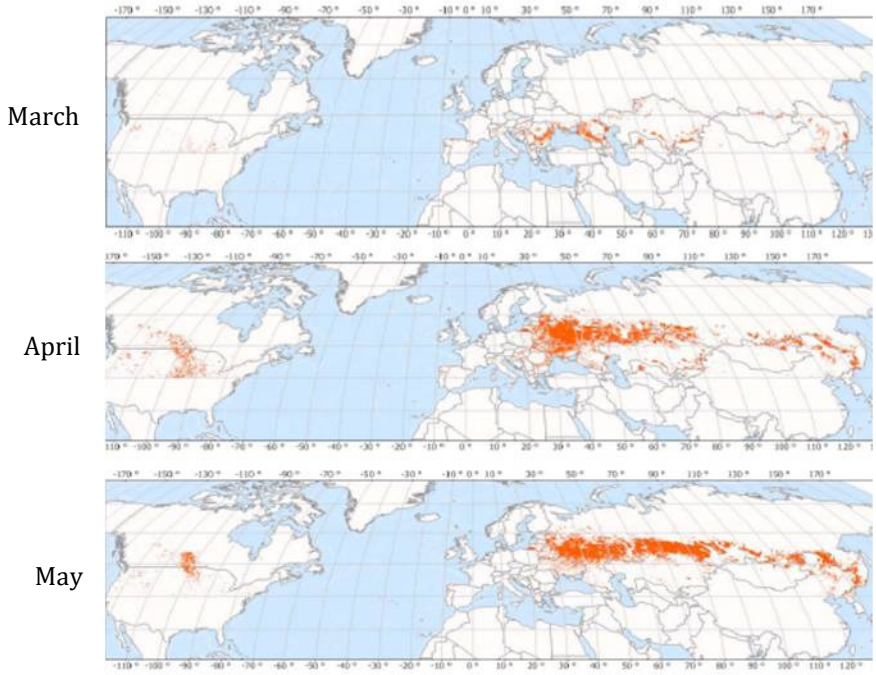


Figure 18. Potential contribution of black carbon from biomass burning to Arctic warming. *Tentative results suggest a stronger contribution from sources in Northern Europe and Asia than for North America. Based on springtime 2007 measurements of black carbon in snow in several Arctic areas, Hegg et al. (2009) found that about 90 percent came from biomass sources. Shown here are satellite-derived locations of open fires in the croplands of Eastern Europe and Russia (2006 Modis Terra Global Land Cover and Burned Area), suggesting substantial biomass burning during the Arctic spring months. About 80 percent of the estimated 50,000 tons of black carbon emitted from biomass sources north of 40°N latitude during these months came from Russia (Pettus, 2009). Note that, on an annual basis, modeling by Flanner et al., (2007) found that 80 percent of Arctic snow deposition was derived from fossil and biofuel sources.*

While research and assessment on the transport and role of biomass burning to deposition and warming in the Arctic will continue, the difficulties in addressing such emissions are substantial. Alternative approaches considered in U.S. air quality management programs for agriculture include improved combustion (Ottmar et al., 2001), conservation tillage, soil incorporation, or hauling the crop residues to central processing sites. Forestry prescribed-burn mitigation options include timing of burns, pile burning to increase burn efficiency, or mechanical removal of material. Converting agricultural wastes to biochar[10] or ethanol are emerging technologies under consideration. In some cases, use of wastes as a fuel could result in net savings. Marginal cost curves produced for EPA suggest that for $15,000 per ton,

[10] Lehman et al. (2006) estimate that 38 to 84 percent of the biomass carbon in vegetation is released during the burn, whereas converting the biomass into biochar by means of simple kiln techniques sequesters more than 50 percent of this carbon in biochar.

about 28,000 tons of black carbon might be reduced in the United States, accompanied by about 165,000 tons of organic carbon reductions (Weitz et al., 2009). How well the relative cost and effectiveness of these approaches might transfer to other regions is unclear.

Based on the suggestive evidence summarized in Figure 18, Arctic climate programs are focusing particular attention on the timing of agricultural fires in Eastern Europe and Russia, northeastern China, and North America (AMAP, 2008). While agricultural fires are banned in Europe, they apparently persist in Eastern Europe and elsewhere. The key issue in the near term is the relative benefit to the Arctic and the extent to which agricultural or forestry burning could be shifted feasibly to a later or much earlier period. An examination of the situation in Russia and Asia suggest a particularly difficult situation, in which the lines between agricultural and wildfires are blurred by changing practices (Pettus, 2009).

Black Carbon Strategy Analyses

Several groups have developed preliminary analyses of global strategies to reduce black carbon emissions (Cofala et al., 2006; Rypdal et al., 2009; Barton et al., 2009). The reports vary in approach but attempt to estimate maximum control approaches and/or least cost strategies. Given the relative costs and emissions above, it is not surprising that the lowest cost alternatives are in Asia, which has high emissions from cookstoves and poorly controlled transportation and small industrial sources. Global maximum feasible reduction estimates for 2030 are about 2.2—2.5 million tons, excluding biomass sources (Cofala et al., 2006; Rypdal et al., 2009). Under their assumptions, maximum feasible reductions in black carbon emissions from domestic cooking and heating are about 0.18 million tons, or less than 15 percent. By contrast, Baron et al. (2009) assumed a stove replacement program that would reduce emissions in China and India alone by 0.22 million tons with an additional 0.1 million ton reduction from switching from coal to charcoal. They also assumed reductions of 1.2 million tons from programs to reduce biomass burning in Africa and South America.

These preliminary global analyses are of interest, but should be followed up by analyses of targeted strategies for regions discussed above, notably the Arctic and the Southern Asia where black carbon plays a disproportionate role in warming and other effects. Work has already begun on assessing Arctic strategies (AMAP, 2008). Improved information on emissions, costs, and effects will serve to improve and expand future assessments.

Considerations for Potential Approaches to Including Sources of Black Carbon in Climate Strategies

This section summarizes some key considerations for policy makers who are weighing the potential role of black carbon as part of a portfolio of strategies to address climate change. In so doing, it recognizes some of the significant differences between CO_2 and other GHGs, which have been the main focus of climate programs to date, and black carbon particles.

Black carbon reductions can provide nearly immediate climate benefits. Because of its short lifetime, black carbon is removed from the atmosphere within weeks after controls take effect. Even soot remaining on snow will lose most of its effect over a period of weeks to months. Combined with its large radiative forcing, this property makes black carbon reductions potentially valuable in the early stages of a comprehensive global climate program (Bond, 2007; Bierbaum et al., 2007; Grieshop et al., 2009).

Black carbon reductions can result in significant regional climate and health benefits. The nature and distribution of black carbon means it can have powerful direct and indirect regional effects on climate beyond those caused by overall GHG-related warming. Because most black carbon remains near high source regions, forcing and other impacts are concentrated there. The effects on climate are not limited to direct forcing but include changes in wind and rainfall patterns, altered clouds, and reduced visibility. Snow darkening can result in a disproportionate warming effect in areas covered by snow and ice. The effect is greatest near source regions (e.g., Eurasia), but still significant in the Arctic. Finally, black carbon and associated organic pollutants are important contributors to millions of premature deaths and a variety of other health effects that occur in regions of moderate to high particle loadings.

The immediacy of climate benefits and varied regional effects of black carbon are critical considerations in developing targeted programs to address several near-term climate concerns:

1) *Warming from sulfate reductions.* Continuing declines in sulfur dioxide emissions to address air pollution related to public health, acid rain, and visibility are reducing the cooling effect of sulfate particles, thus enhancing the net warming caused by GHGs and black carbon. Because this warming effect is also nearly immediate, even crash programs to reduce CO_2 could not act quickly enough to offset it.

2) *Rapid shrinkage of Arctic sea ice and snow.* Transported and deposited soot appears to play a major role in snow and ice melting in this critical region. Uncertainties about net forcing for some source categories are diminished in this case. Evaluation of source contribution and reduction alternatives for black carbon is a priority for developing near-term strategies to slow the rate of change until more comprehensive global GHG reductions can take effect.

3) *Retreat of the Himalayan glaciers.* The multiple effects of high levels of black carbon and other particles in combination with GHGs all may be significant in this threat to the water supply for large portions of Asia. Mechanisms plausibly linked to black carbon include altered temperature gradients, reduced surface evaporation, potential reductions in monsoon rains, and darkening of glacier ice. At the same time, implementing the most cost-effective control strategies for sources in this heavily populated region would produce significant health benefits.

While a strong scientific consensus exists regarding the effects and control of GHGs, a number of uncertainties remain that limit the precision of answers to questions regarding the cost and efficacy of control for sources of black carbon. Uncertainties in emissions, modeling, ambient data, and indirect effects are all of concern and are important to address, both for advancing scientific understanding, and for assessing strategies. *Nevertheless, it is now clear that sources of black carbon have a substantial effect on climate and that ignoring this could lead to suboptimal assessments and strategies.*

GHG-based strategies could be enhanced, at a minimum, by being cognizant of potential associated benefits or adverse effects of changes in black carbon and other particles. One example given above is moving light duty vehicles from gasoline to diesel to save fuel and reduce CO_2. Without the addition of particle filters motivated by air pollution programs to remove the increased black carbon, much of the CO_2 benefit would be lost. Coordination between climate strategies and air pollution programs could reduce both GHG and black carbon emissions, as in the case of anti-idling rules, biodiesel fuels, and truck stop electrification programs.

Industrialized nations have already developed and applied technologies to reduce black carbon and associated particles; technologies are also available to address emissions specific to developing nations. Combustion improvements and particle controls have virtually eliminated black carbon from coal combustion in point sources. Technologies to reduce black carbon from mobile sources are required to meet standards for new on- and off-road diesel equipment. Air pollution regulations have also required cleaner woodstoves, and curtailed open burning in areas where standards are not met. In addition, viable alternatives exist for reducing the emissions of residential biofuel cooking and heating and of small, poorly controlled industrial operations.

The large number and nature of many small, dispersed sources of black carbon present difficulties for developing and implementing control approaches. Black carbon emissions are dominated by numerous small sources including residential cooking, on- and off-road vehicles, and biomass burning. Without concerted and targeted efforts, it may be difficult to realize the benefit of near-term reductions in the critical target areas above where it appears to be of most importance.

The cost-effectiveness of control and alternative technologies for black carbon climate programs varies significantly by source application. Without improvements in economies of scale, some black carbon controls may not compete with CO_2 reductions in terms of cost-effectiveness for addressing global-scale warming. Unlike the case for most air pollution controls, costs for diesel retrofits appear to have increased with time, and CO_2e costs per ton are higher than those expected in early stages of CO_2 trading programs. It is not clear whether more widespread adoption of diesel retrofit technologies will eventually reduce these costs. The benefits of such programs increase, however, if a premium is placed on more rapid reductions in targeted strategies (e.g., use of a 20-year or shorter GWP), or if health benefits are also considered.

Conclusions

Until recently, control of black carbon sources has been given little or no consideration in discussions regarding strategies to address global climate change. In recent years, however, it has become increasingly clear that sources of this pollutant have significant effects on climate on a global and regional scale. To the extent that sources can be controlled in the near term, reductions in black carbon can produce faster results than reductions in GHG emissions. Whether black carbon is second or third most important climate driver, however, GHGs are collectively more significant. Controlling CO_2 and other GHGs will be the primary means for reaching long-term goals of stabilizing global climate and limiting temperature increases, but black carbon reductions also have a role to play in comprehensive strategies.

A UN Scientific Expert Group concluded that avoiding an increase of 2°C to 2.5°C "would require very rapid success in reducing emissions of CH_4 and black soot worldwide, and it would require that global CO_2 emissions level off by 2015 or 2020 at not much above their current amount, before beginning a decline…" thereafter (Bierbaum et al., 2007). Grieshop et al. (2009) have suggested black carbon mitigation strategies as a 16th climate strategy "wedge" in addition to the 15 GHG mitigation strategies proposed by Pacala and Socolow (2004). These authors recognize the inherent uncertainties and challenges outlined above; they believe enough is known about the likely climate benefits for some source categories, the speed of the response to reductions, and the substantial health benefits to prompt near-term action.

An alternative to the global approaches suggested by these experts would focus on the unique distribution and properties of black carbon that greatly increase its apparent impact on warming and rainfall patterns in the Tibetan Plateau and other Eurasian glacier regions and the Arctic. As discussed above, targeted strategies directed at key sources that affect these regions would benefit climate globally, but would also focus the rapid response of black carbon strategies on key near-term climate "tipping points." Given the dispersed nature of the principal source categories, targeted approaches also have a better chance of producing results over the next decade. In the meantime, research must continue to reduce uncertainties in emissions, modeling, monitoring, indirect effects, and meteorology and in developing lower cost, feasible control approaches for key source categories.

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John Bachmann, Vision Air Consulting, LLC
Formerly Associate Director for Science/Policy and New Programs, Office of Air Quality Planning and Standards, EPA