Chapter 6

Benefits of Reducing Black Carbon Emissions

6.1 Summary of Key Messages

- Mitigation of BC offers a clear opportunity: continued reductions in BC emissions can provide significant near-term benefits for climate, public health, and the environment.

- It is generally impossible to reduce BC in isolation from other co-pollutants: most BC mitigation strategies involve reductions in total emissions of fine particles, including other $PM_{2.5}$ constituents. Fortunately, all control measures that reduce $PM_{2.5}$ pollution—including BC and other constituents—will achieve substantial health benefits. Therefore, mitigation strategies targeting BC that also reduce total direct $PM_{2.5}$ emissions could potentially result in hundreds of thousands of avoided premature deaths each year. The health benefits alone may be large enough to justify mitigation in many regions and sectors.

  – Because a variety of PM constituents are associated with adverse health impacts, significant health benefits are anticipated to result from reducing exposure to PM containing BC, regardless of the precise chemical composition of the emissions mixture.

  – Controls on direct $PM_{2.5}$ emissions (including BC) can be particularly beneficial since they are more co-located with population than other PM components. According to U.S. EPA estimates, the benefits from control of direct $PM_{2.5}$ emissions are 7 to 300 times greater than the benefits per ton estimated for reductions of PM precursors such as NO_x and SO_x.

  – The magnitude of human health benefits of emissions reductions depends both on how much exposure is reduced and the size of the affected population. The largest health benefits from $PM_{2.5}$ including BC control strategies will be achieved in areas near the emissions source and where exposure affects a large population.

  – Programs to reduce $PM_{2.5}$ in the United States and in other developed countries have greatly reduced the negative health impacts of $PM_{2.5}$, including BC. New programs introduced for mobile and stationary sources will continue to reduce $PM_{2.5}$-related health impacts in the United States and the countries that implement them over the next several decades.

  – The largest opportunities for achieving health benefits of BC mitigation measures are in lesser developed countries, due to high emissions co-located with large populations, particularly in South and East Asia.

- Estimating the climate benefits of mitigation strategies is more challenging than health benefits estimation because key scientific issues remain unresolved. Despite uncertainties in the magnitude of effects, the literature suggests climate benefits could be achieved through some mitigation measures.

  – BC reductions are expected to reduce the rate of warming soon after measures are implemented, though the full climate response may take several decades to fully manifest. In sensitive regions (e.g., the Arctic), or in regions of large emissions (e.g., South and East Asia), additional benefits may include slowing the rate of ice, snow, and glacier melt, and reversal of adverse precipitation changes.

  – Achieving climate benefits is most likely to result from the control of emissions from BC-rich sources such as diesel engines, cookstoves, brick kilns and coke ovens.

  – BC mitigation alone cannot change the long-term trajectory of global warming, which is driven by CO_2 emissions. However, as illustrated by a recent UNEP/WMO analysis, controlling current BC and long-lived GHGs in concert would greatly improve the chances of limiting global temperature rise below 2°C relative to pre-industrial levels.

   - BC mitigation may have particular benefits for the Arctic and the Himalayas, two regions that are particularly sensitive to BC deposition. In the Arctic, both global and high-latitude BC reductions can provide climate benefits. The most effective emissions reductions per unit of emissions will come from within- or near-Arctic sources, but overall reductions in global BC emissions will be critical to slowing the rate at which the Arctic is warming and melting. Slowing the rate of change may avoid reaching certain global tipping points as discussed in earlier chapters. In the Himalayan region, a range of local measures is likely to provide climate benefits, including sizable benefits for radiative forcing, ice/snow melt, precipitation and surface dimming.

- Limiting BC emissions also is expected to provide a number of environmental benefits, including improved visibility, reduced surface dimming, reduced impacts on ecosystems, and less damage to building materials.

- More research is needed on the benefits of individual control measures in specific locations to support policy decisions made at the national level. Research is also needed to design approaches to valuing the climate impacts of BC directly, and to incorporate those approaches into useful metrics for evaluating policy decisions, similar to the social cost of carbon (SCC).

6.2 Introduction

This chapter summarizes available information regarding the potential public health, climate and environmental benefits of reducing BC emissions, both in general and from particular economic sectors. The literature on the health benefits of reductions in fine particles (including BC) is well-developed, particularly in the United States where emissions control programs have been evaluated extensively. These analyses provide a high degree of confidence that BC mitigation strategies will produce significant public health benefits, not just from the BC reduction, but also from the reduction in co-emitted gaseous and particulate pollutants as well. As BC effects on climate are less certain than on health, there is also less certainty about the climate benefits of BC mitigation. Although the body of literature on climate benefits is limited, it provides important insights regarding which strategies are most likely to provide climate benefits. Non-climate environmental benefits of BC reductions are also less certain than health benefits, but the literature on $PM_{2.5}$ impacts provides important qualitative information regarding the likelihood of such benefits. It is important to note that a quantitative assessment of the benefits of specific mitigation measures was not conducted for this report due to time and resource constraints. Further analysis would be necessary to quantify the public health, climate and environmental benefits of specific BC reduction strategies, either individually or in combination.

6.3 Public Health Benefits of Reducing Black Carbon Emissions

All control measures that reduce $PM_{2.5}$ emissions, of which BC is a component, are virtually certain to achieve health benefits. The adverse health impacts of $PM_{2.5}$ are well documented in the scientific literature, previously discussed in Chapter 3 and in EPA's recent PM ISA (U.S. EPA, 2009a). The well established linkage between $PM_{2.5}$ and health effects is important, because mitigation strategies aimed at reducing BC almost always involve reductions in co-pollutants, including other PM constituents or precursors, as well as BC. BC is emitted in a mixture of other pollutants that are also associated with negative health effects, including primary particulate matter (including OC), precursors of secondary particulate matter (SO_2, NO_x, NH_3), and ozone precursors (NO_x, CO, VOCs). Reductions in all of these pollutants can provide human health benefits. Though the literature on differential toxicity of $PM_{2.5}$ components and mixtures is currently inconclusive, studies continue to provide evidence that many $PM_{2.5}$ constituents are associated with adverse health impacts, as discussed in Chapter 3. Because of the well documented health impacts of $PM_{2.5}$, there is high likelihood that BC mitigation strategies that reduce $PM_{2.5}$ will produce public health benefits. This section summarizes what is known about the health benefits of BC emissions reductions in the United States and globally.

6.3.1 Health Benefits in the United States

Historically, the United States has been quite successful in achieving significant $PM_{2.5}$ reductions through air quality protection programs such as attaining the $PM_{2.5}$ NAAQS and implementing a variety of mobile source rulemakings. These reductions yield large human health benefits. As discussed in Chapter 4, however, emissions of BC in the United States are still fairly substantial. Additional control programs, largely those affecting mobile diesel engines, are expected to achieve further BC reductions by 2030 with significant public health benefits (see Chapter 8). EPA's analyses of these benefits provide useful information regarding the potential public health improvements that can be achieved via strategies targeting direct emissions of $PM_{2.5}$, including BC. Below, we describe how the benefits of policies that reduce atmospheric pollutant loads are developed, and discuss in more detail specific estimates of the health benefits that $PM_{2.5}$ mitigation policies can help achieve.

6.3.1.1 Methods for Estimating the Health Benefits of Reducing $PM_{2.5}$

Peer-reviewed methods for estimating the public health benefits of $PM_{2.5}$ emissions reductions have been used in a variety of settings and the sophisticated models and techniques developed for application in the United States have been refined by EPA over the course of several decades. These methods rely upon atmospheric models to translate emissions changes into concentration changes, and epidemiologically derived concentration-response functions to calculate the change in a health endpoint attributable to the concentration change. Valuation techniques are then used to quantify the economic impact of the health benefits, with the total monetized benefit calculated as the sum of the values for all non-overlapping health endpoints. Health benefits are often monetized using the Value of a Statistical Life (VSL), which is determined by studies of individuals' willingness to pay (WTP) for reducing their risk of mortality. This approach is the standard method for assessing benefits of environmental quality programs and has been used widely in EPA regulatory documents (e.g., U.S. EPA, 2006c), as well as in the peer-reviewed literature (e.g., Levy et al., 2009; Hubbell et al., 2009; Tagaris et al., 2009).

Air pollution affects a variety of health endpoints, as discussed in Chapter 3. For some, currently available data are insufficient to enable quantification or monetization of effects. Table 6-1 summarizes the health endpoints that have been included in recent EPA $PM_{2.5}$ benefit assessments. The table indicates which effects have been quantified and monetized (left column), and which are discussed only qualitatively (right column).

Overall, the $PM_{2.5}$ control program in the United States has proven highly protective of public health. Multiple studies estimate significant reductions in $PM_{2.5}$-related mortality and morbidity since the implementation of the Clean Air Act (CAA). In a recent study, EPA also estimated that programs implemented as a result of the 1990 CAA Amendments have avoided about 160,000 annual premature adult deaths by 2010, and will avoid 230,000 by 2020 (Table 6-2). Direct $PM_{2.5}$ reductions specifically have been associated with 22,000 to 60,000 annual avoided premature deaths between 2000 and 2007 (Fann and Risley, 2011). Improvements in particulate air pollution, particularly in urban areas, have also been estimated to contribute 15% of a 2.72 year increase in average life expectancy among 211 counties between 1980 and 2000 (Pope et al., 2009).

6.3.1.2 The Potential Benefits of Further Mitigation of $PM_{2.5}$ (Including BC) Emissions

Despite significant improvements, the health burden of $PM_{2.5}$ in the United States is still substantial. Based on 2005 air quality data and population, Fann et al. (2011) estimated that about 130,000 annual premature deaths and 19% of all ischemic

Table 6-1. $PM_{2.5}$ Health Endpoints Included in EPA's Regulatory Impact Analyses. (Source: U.S. EPA, 2006, Table 5-2)

Quantified and Monetized $PM_{2.5}$ Health Endpoints	Un-Quantified and Non-Monetized $PM_{2.5}$ Health Endpoints
Premature mortality based on cohort study estimates and expert elicitation estimates	Low birth weight, pre-term birth and other reproductive outcomes
Hospital admissions: respiratory and cardiovascular	Pulmonary function
Emergency room visits for asthma	Chronic respiratory diseases other than chronic bronchitis
Nonfatal heart attacks (myocardial infarctions)	Non-asthma respiratory emergency room visits
Lower and upper respiratory illness	UVb exposure (+/-)
Minor restricted activity days	
Work loss days	
Asthma exacerbations (among asthmatic populations)	
Respiratory symptoms (among asthmatic populations)	
Infant mortality	

heart disease-related deaths nationwide were attributable to $PM_{2.5}$ exposure. Fortunately, a number of additional $PM_{2.5}$ control programs that will help to control $PM_{2.5}$ (including BC) over the next several decades have already been adopted and are expected to yield significant health benefits. In the illustrative regulatory impact analysis conducted by EPA in 2006 for the revised $PM_{2.5}$ NAAQS, benefits

Table 6-2. Changes in Key Health Effects Outcomes in the United States Associated with $PM_{2.5}$ Resulting from the 1990 CAA Amendments. (Source: U.S. EPA (2011a) Table 5-6, adjusted from 2006$ to 2010$)

Health Effect Reductions	Year 2010		Year 2020	
	Incidence Avoided	Valuation (millions 2010$)	Incidence Avoided	Valuation (millions 2010$)
Adult Mortality	160,000	$1,300,000	230,000	$1,800,000
Infant Mortality	230	$2,100	280	$2,700
Chronic Bronchitis	54,000	$26,000	75,000	$39,000
Acute Bronchitis	130,000	$66	180,000	$100
Acute Myocardial Infarction	130,000	$15,000	200,000	$23,000
Hospital Admissions, Cardiovascular	45,000	$1,400	69,000	$2,200
Lower Respiratory Symptoms	1,700,000	$32	2,300,000	$45
Upper Respiratory Symptoms	1,400,000	$45	2,000,000	$65
Asthma Exacerbation	1,700,000	$97	2,400,000	$140
Lost Work Days	13,000,000	$2,200	17,000,000	$2,900

Notes:

1. EPA's estimates of reductions in respiratory hospital admissions, respiratory emergency room visit, and minor restricted activity days are not included here, because the 2011 report presented these estimates only as combined totals for both $PM_{2.5}$ and ozone.
2. Estimates reflect annual incidence avoided and valuation for reductions in direct $PM_{2.5}$ and $PM_{2.5}$ precursors.

Table 6-3. List of Benefits, Costs, and Benefit to Cost Ratios for U.S. Rules with Direct PM Reductions (Billions 2010$).[a] (Source: U.S. EPA)

Rule (by Sector)	Annual Benefits[b]	Annual Costs	Benefit/Cost Ratio	Benefit Year
Transportation				
Light Duty Tier 2	$34	$7.2	4.7	2030
Heavy Duty 2007	$92	$5.5	16.7	2030
Non-road Diesel Tier 4	$105	$2.5	41.5	2030
Locomotive & Marine Diesel	$9.9–23.8	$0.8	13.1–31.4	2030
Ocean Vessel Strategy	$119–292	$3.4	35.5–87.1	2030
Stationary Sources				
2006 PM NAAQS[c]	$22	$7.1	3.1	2020
Cement NESHAP	$8.3–20.1	$1.01–1.04	8.2–19.4	2013
Stationary Spark Ignition RICE NESHAP	$0.52–1.2	$0.26	2–4.7	2013
Stationary Compression Ignition Engine NESHAP	$0.95–2.3	$0.37	2.5–6.2	2013

[a] Rules include a combination of direct $PM_{2.5}$ and PM precursor reductions. These estimates have been adjusted from the dollar years in the original analysis to 2010$.

[b] 3% discount rate used for benefit estimates.

[c] Estimates of benefits and costs for the PM NAAQS are illustrative since individual states will make the decisions about actual control strategies implemented to comply with the NAAQS.

Table 6-4. Direct $PM_{2.5}$ National Average Benefits per Ton Estimates by Source Category for the United States (3% Discount Rate, Thousands of 2010$). (Source: *http://www.epa.gov/air/benmap/bpt.html*, based on method described in Fann et al., 2009)

Source Category	Monetized Benefit Per Ton in 2015	Monetized Benefit Per Ton in 2020	Monetized Benefit Per Ton in 2030
Area Source			
Pope et al. (2002)	$360	$400	$480
Laden et al. (2006)	$880	$970	$1,200
Mobile Source			
Pope et al. (2002)	$280	$300	$360
Laden et al. (2006)	$680	$740	$890
EGU and Non-EGU			
Pope et al. (2002)	$230	$250	$290
Laden et al. (2006)	$560	$610	$710

Notes:

1. These estimates have been adjusted from 2006$ to 2010$.
2. These are U.S. national average estimates, and these estimates may vary for different geographic locations in the country.

are estimated to be $22 billion per year in 2020 (2010$) (U.S. EPA, 2006c). Benefits for the non-road diesel rule have been estimated at $105 billion per year in 2030 (2010$) (U.S. EPA, 2004a). The benefits for these and other rules with direct $PM_{2.5}$ reductions are shown in Table 6-3, along with the costs and benefit-cost ratios for each rule.[1] While the relationship between benefits and costs for $PM_{2.5}$ reductions is discussed in more detail in Chapter 12, it is useful to note that quantified benefits exceed costs for each rule, often by a significant margin. For the nonroad diesel rule, quantified benefits are estimated to be over 41 times greater than costs in 2030.

As a shorthand approach for assessing potential health benefits resulting from different mitigation strategies when air quality modeling is unavailable, Fann et al. (2009) developed values of monetized health benefits per ton of emissions reduced for SO_2, NO_x, and direct $PM_{2.5}$ in the United States.[2] For directly emitted $PM_{2.5}$ (including BC) from all sources, these benefits (on average) range from $230,000 to $880,000 per ton of $PM_{2.5}$ reduced in 2015 (2010$).[3] While EPA has not separately estimated the benefits per ton for BC reductions specifically, Table 6-4 illustrates the results for reductions in total direct carbonaceous emissions (i.e., BC + OC) for 2015, 2020, and 2030. It is clear that controls on all sources of direct $PM_{2.5}$ can produce substantial public health benefits in the United States; furthermore, these benefits are 7 to 300 times greater than the benefits-per-ton estimated for reductions of other PM precursors such as NO_x and SO_x (Fann et al., 2009), indicating that controls on direct $PM_{2.5}$ may be particularly effective for protecting public health. The authors attribute this largely to the fact that carbonaceous particles tend to be emitted in close proximity to population centers.

These $PM_{2.5}$ monetized benefit-per-ton estimates are useful for evaluating the benefits associated with incremental $PM_{2.5}$ air quality improvements in the United States and represent the premature mortality and premature morbidity benefits associated with reducing one ton of $PM_{2.5}$ from a specific source. As discussed above, these estimates are based upon the methodology described in

[1] The benefits, costs, and associated benefit-cost ratios relate to reductions in not only direct $PM_{2.5}$ but also in other controlled co-pollutants. EPA did not estimate the costs and benefits of controls on direct $PM_{2.5}$ or specific constituents separately.

[2] The benefit-per-ton estimates found in Fann et al. (2009) reflect a specific set of key assumptions and input data. As EPA updates these underlying assumptions to reflect the scientific literature, the benefit-per-ton estimates are re-estimated and are available at: *http://www.epa.gov/air/benmap/bpt.html*.

[3] According to Fann et al. (2009), the wide range in these benefit-per-ton estimates reflects several key sources of heterogeneity, including variability in source parameters which affect pollutant dispersion and human exposure, and variability in location-specific factors such as population density and baseline health status. In addition, the estimates vary depending on which morbidity and mortality effect estimate are utilized from the underlying epidemiological references.

Fann, et al. (2009) that used an innovative reduced-form air quality model to estimate changes in ambient $PM_{2.5}$ concentrations resulting from a variety of emissions control strategies applied to different classes of emissions sources. The estimates originally developed by Fann, et al. (2009) have been updated to incorporate revised VSL estimates (*http://www.epa.gov/air/benmap/bpt.html*). The monetized mortality and morbidity benefits of changes in ambient $PM_{2.5}$ were estimated using the Environmental Benefits Mapping and Analysis Program (Abt Associates, 2008) and developed for specific U.S. urban areas and the United States as a whole.[4]

While EPA strives to incorporate quantitative assessments of uncertainty in the health impacts estimates, there are aspects for which only qualitative assessments are possible. Key assumptions underlying the estimates are presented in detail in the regulatory impact assessments for each regulation. Typically, health impact assessments include uncertainty in the concentration-response function but are unable to include uncertainty in emissions, simulated concentrations, and projected population and mortality rates.

6.3.2 Global Health Benefits

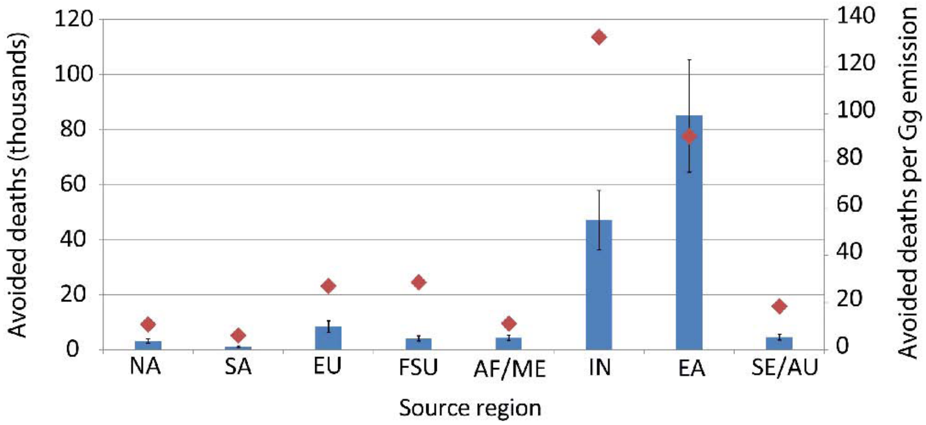
Though the United States has already made great strides toward reducing BC through its efforts to reduce $PM_{2.5}$ emissions, BC emissions remain very high in some parts of the world due to industrial production, residential burning of solid fuel, and transportation (see Chapter 7). Furthermore, unlike in the United States and Europe, where additional controls are already planned for key source categories such as mobile diesel engines, emissions from many other international sources are not yet subject to plans for control. As a result, the largest remaining achievable increment of public health benefits from controls on BC is international, particularly in South and East Asia, where large populations are exposed to high concentrations. While a growing body of literature examines the climate benefits of controlling BC emissions globally (see section 6.4), only a few studies have examined the associated health benefits. For these few studies, the estimated public health benefits are very large, and for many control measures the benefits greatly exceed the costs of controls, suggesting that these reduction measures will be advantageous for society independent of the level of climate benefits achieved. This section (1) describes studies that have estimated the potential health benefits that can be achieved through mitigating BC emission and (2) discusses approaches that have been used to value the health benefits that could be achieved on a global scale.

6.3.2.1 Estimating the Benefits of Global BC Mitigation

In a study focused specifically on the health impacts of BC reductions, Anenberg et al. (2011) estimated that halving anthropogenic BC emissions (but not any co-emissions) globally would avoid 157,000 (95% confidence interval, 120,000-194,000) annual premature deaths worldwide. Over 80% of these health benefits occurred in East Asia (China; 54%) and South Asia (India; 31%), where large populations are exposed to high concentrations (see blue bars in Figure 6-1). Halving all anthropogenic BC emissions in each major world region individually demonstrated that the vast majority of avoided deaths from halving BC emissions occur within the source region, with very little impact from extra-regional emissions. This is because BC impacts on health are driven by surface concentrations where humans live. BC emissions that are transported to other regions are usually conveyed at high altitudes, where they may have more widespread impacts on climate, but impact human health less. Per unit of emissions, the mortality impact of BC emissions was estimated to be 50% larger for South Asia than for East Asia (see red diamonds in Figure 6-1). This is likely because emissions changes in East Asia have smaller impacts on concentrations and because mortality rates are higher in South Asia.

Anenberg et al. (2011) found that halving global residential, industrial, and transportation emissions contributed 47%, 35%, and 15% of the avoided deaths, respectively, from halving all anthropogenic BC emissions. Residential and industrial sector contributions to global BC-related mortality are each 1.2 times greater than their contributions to global BC emissions, owing to their co-location with dense populations, mainly in developing regions. In contrast, the contribution of transportation emissions to mortality is 40% lower than the contribution of that sector to global BC emissions, since transportation emissions are more evenly distributed among developing and less populated developed regions. Avoided deaths were likely underestimated for the residential sector since indoor exposure was excluded from the study. Figure 6-2 shows that while the industrial and residential sectors in East Asia have the greatest BC emissions ("mitigation potential"), all three sectors in South Asia have the greatest estimated

4 For further information about the underlying methodologies and analytical assumptions used to develop these estimates, as well as, relevant uncertainties involved in the estimates see Fann, et al. (2009) and EPA regulatory impact analyses including the SO_2 NAAQS RIA (U.S. EPA, 2010h) and the Portland Cement NESHAP RIA (U.S. EPA, 2010b) available at *http://www.epa.gov/ttn/ecas/ria.html*.



Abbreviation	Region
NA	North America
SA	South America
EU	Europe
FSU	Former Soviet Union
AF/ME	Africa/Middle East
IN	South Asia (India)
EA	East Asia (China)
SE/AU	Southeast Asia/ Australia

Figure 6-1. Estimated Global Mortality Benefits of Black Carbon Reductions. Global annual avoided premature cardiopulmonary and lung cancer deaths (thousands; blue bars) and avoided premature deaths per Gg BC emissions reduced (red diamonds), for halving anthropogenic BC emissions in each source region relative to the base case. (Anenberg et al., 2011)

Note:
Confidence intervals (95%) reflect uncertainty in the Concentration Response Function only.

mortality impacts per unit of emissions ("mitigation efficiency"). Outside of South Asia and East Asia, estimated mitigation efficiency is greatest for the Former Soviet Union, Southeast Asia/Australia, and Europe, while mitigation potential is likely greatest for the residential sector in Africa/Middle East and for the transportation sector in Europe and North America.

It is important to note that these estimates understate the full public health benefits that would be achieved by reductions in global BC emissions. Since controls to reduce BC will generally reduce other directly emitted particles as well, halving global BC emissions would likely result in far larger changes in overall $PM_{2.5}$ emissions. In fact, Anenberg et al. (2011) estimated that halving global anthropogenic OC emissions along with BC resulted in eight times more avoided premature deaths annually than halving BC alone. Nevertheless, this study demonstrates that BC mitigation efforts are likely to be more effective at reducing mortality in some regions than others, largely driven by population exposure. Although the coarse grid resolution (~170 km on a side) used by Anenberg et al. (2011) was unable to capture fine-scale spatial gradients in population and concentration, emissions from different sectors result in different exposure patterns. Therefore, the health response to controlling emissions from different regions and from different source sectors is likely to vary. Finer scale models can be used to investigate how different mitigation strategies impact health within individual world regions.

While Anenberg et al. (2011) examined broad percentage decreases in BC emissions from individual source regions and sectors, actual mitigation measures will affect the full mixture of emissions from individual sources. Currently, the most comprehensive assessment of more realistic emissions control measures is the *Integrated Assessment of Black Carbon and Tropospheric Ozone* sponsored by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Using an integrated modeling approach addressing a range of co-emitted pollutants, the UNEP/WMO Integrated Assessment identified a small number of emissions reduction measures that would achieve major benefits for near-term climate change. This suite of measures included both BC reduction measures and methane reduction measures. For BC, the assessment modeled the impact of both "technical measures," such as improving coke ovens and brick kilns and increasing use of diesel particulate filters, and "non-technical measures," such as eliminating high-emitting vehicles, banning open burning of agricultural waste, and eliminating biomass cookstoves in developing countries. Specifically, the Assessment evaluated the health benefits of the following BC measures:

- Use of diesel particle filters as part of a Euro VI package for on-road and off-road diesel vehicles

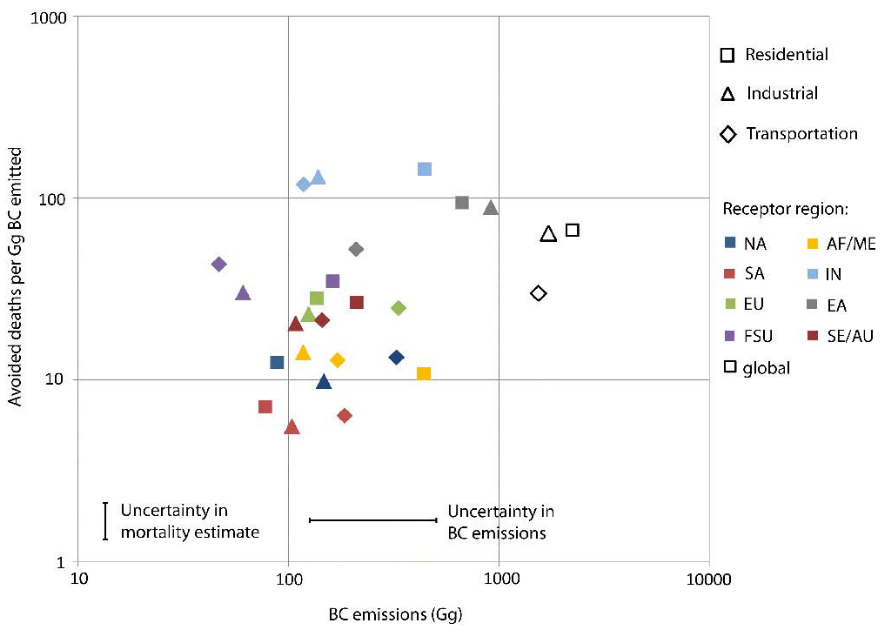


Figure 6-2. Annual Avoided Premature Cardiopulmonary and Lung Cancer Deaths Per Unit BC Emissions Reduced ("mitigation efficiency") versus Total BC Emissions (Gg; "mitigation potential") for Particular Source Sectors within Each Region. (Anenberg et al., 2011)

Notes:

1. Avoided deaths are estimated in the three simulations where global emissions in each sector are halved, and shown for each receptor region; these deaths are compared with emissions from each region, assuming that deaths from inter-regional transport are negligible.
2. Uncertainty in the mortality estimates is calculated from the uncertainty in the CRF only (~22% and 56% from mean for cardiopulmonary and lung cancer mortality).
3. Uncertainty in BC emissions is assumed to be a factor of 2 from the central estimate (Bond et al., 2004; 2007).
4. Since these uncertainties are factor differences from the central estimate, they are identical for each data point.

- Introduction of clean-burning cook stoves for cooking and heating in developing countries
- Replacement of traditional brick kilns with vertical shaft kilns and Hoffman kilns
- Elimination of high-emitting vehicles in on-road and off-road transport (excluding shipping)
- Ban of open field burning of agricultural waste
- Substitution of clean-burning cook stoves using modern fuels for traditional biomass cook stoves in developing countries

Together, these BC measures were estimated to reduce global anthropogenic BC emissions by 75%, along with substantial reductions in co-emitted OC, NO_x, and CO.

The UNEP/WMO Assessment estimated that fully implementing these measures by 2030 would avoid 0.6-4.4 million $PM_{2.5}$ related premature deaths and 0.04-0.52 million ozone-related premature deaths annually around the world, based on 2030 population projections (Shindell et al., 2012; UNEP and WMO, 2011b). Consistent with the results of Anenberg et al. (2011), over 80% of the health benefits occur in Asia. Figure 6-3 shows that implementing the BC and methane measures would reverse the trend of increasing air pollution-related deaths in Africa and South, West, and Central Asia (although methane and BC measures are shown together here, BC measures contribute ~98% of the total health benefits). Figure 6-3 also shows the additional benefits achievable in areas already making progress. The study also found that the substantial health benefits of the joint air quality/ climate mitigation measures examined occur regardless of whether measures to reduce long-lived GHG have been implemented. A follow-on study to the UNEP/WMO Assessment found that in Africa, Asia, and Latin America and the Caribbean, improved biomass cookstoves would generate the greatest health benefit of all the measures examined, with substantial additional benefits from mitigation measures for the transportation sector (UNEP, 2011). In Europe and North America, switching to pellet stoves from current domestic wood-burning technologies was estimated to deliver the greatest health benefit. The study also found that banning the burning of agricultural crop residues would produce a small benefit in all regions.

One additional study examined the potential health benefits of global reductions in vehicle emissions specifically, accounting for the full

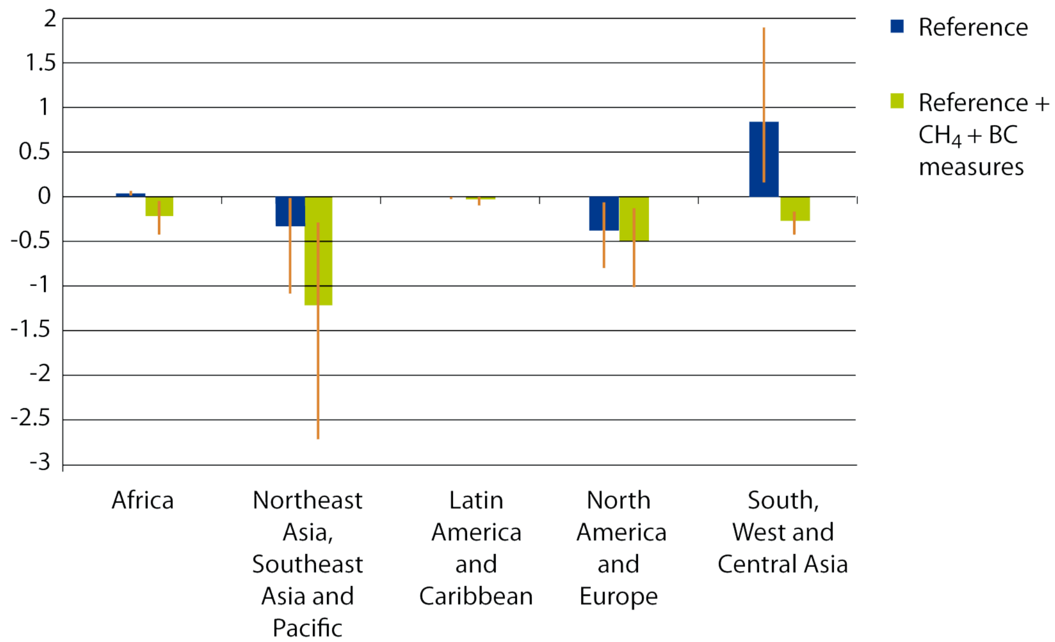


Figure 6-3. Comparison of Premature Mortality by Region (millions of premature deaths annually), showing the change in 2030 in comparison with 2005 for the reference scenario emission trends and the reference plus methane and BC measures. The lines on each bar show the range of estimates. Over 98% of the benefits were attributed to the BC measures. (Source: UNEP and WMO, 2011b)

mixture of emissions affected by control measures (Shindell et al., 2011). Emissions from on-road motor vehicles, including cars, trucks, and motorcycles, are growing rapidly in many countries, due to rising personal vehicle ownership and usage. Shindell et al. (2011) assessed the potential health benefits of imposing existing gasoline and diesel European vehicle emissions standards in developing regions. Specifically, the study examined the adoption of Euro 6 vehicle standards in China and India, Euro 4 vehicle and Euro 3 motorcycle standards in Africa and the Middle East, Euro 6 vehicle and Euro 3 motorcycle standards in Brazil, and Euro 3 motorcycle standards in the rest of Latin America, based on the authors' judgment of local financial, technical, and institutional capacity. The European standards are more stringent than the standards currently planned in these regions. Imposing these standards was estimated to avoid 120,000-280,000 premature $PM_{2.5}$ and ozone-related deaths worldwide, based on 2030 population, largely resulting from local emissions controls. Small benefits were also seen in areas with no additional local emission controls due to long-range transport of ozone and $PM_{2.5}$ in the atmosphere. The study concluded that tighter vehicle emissions standards are likely to lead to significant health benefits, in addition to climate benefits in most cases.

In addition to the BC and sector-specific studies described above, there is a small but emerging body of literature assessing the global health benefits of $PM_{2.5}$ emissions reductions. The results from additional global and international studies are summarized in Appendix 3. Many of these studies estimate the avoided premature deaths associated with reductions in BC and other $PM_{2.5}$ constituents, while other studies attempt to compare the costs and benefits of potential mitigation strategies. These studies indicate that a large number of premature deaths can be avoided annually by undertaking strategies to reduce BC emissions (Shindell et al., 2011; 2012; Anenberg et al., 2011; Wilkinson et al., 2009; Saikawa et al., 2009; Jacobson, 2010). The studies that include a benefit-cost comparison show that estimated human health benefits significantly exceed the estimated costs for certain BC mitigation strategies (Smith and Haigler, 2008; Kandlikar et al., 2009; Baron et al., 2009). Thus, BC reductions appear advantageous to society independent of the level of climate benefits achieved. This is particularly true of sources associated with high human health exposures, such as cookstoves (which are often used indoors in confined spaces) and vehicles located in densely populated areas.

Valuing the global health benefits of emissions controls is difficult due to limited data on willingness to pay for reducing mortality risks. In general, studies valuing reduced mortality around the world have used two methodologies. In the first, a uniform VSL, generally from U.S. or European studies, is applied to avoided premature deaths in all countries, regardless of income or other economic disparities. While ethically appealing, willingness-to-pay is a function of income and thus would reasonably be expected to vary around the world. The second approach is to adjust VSLs from the developed world by measures of income or other economic welfare in other countries, for example income elasticity. While this method is often criticized because it seems to imply that lives in different countries are valued at different levels, it accounts for differences in income levels and is therefore often the preferred approach among economists. This approach still has limitations, including the inability to account for differences in social values and culture.

Acknowledging the advantages and disadvantages of these valuation approaches, the UNEP/WMO Assessment and Shindell et al. (2011) reported the monetized health benefits of mitigation measures using both methods (UNEP and WMO, 2011a). The UNEP Assessment estimated the monetary value of the ozone and $PM_{2.5}$-related premature deaths avoided as a result of the methane and BC measures was $1.7-10.9 trillion in 2010 $US. Consistent with the mortality results, the vast majority of the monetized health benefits resulted from the BC measures. Shindell et al. (2011) estimated that the global health benefits of imposing tighter vehicle emissions standards in the developing world are valued at $0.7-2.6 trillion in 2010 $US. Since the majority of the health benefits resulting from these emissions control measures occur in developing countries, the income-adjusted VSL approach leads to lower valuation estimates compared with the uniform VSL approach.[5] Shindell et al. (2012) conclude that since about half of the benefits of all BC mitigation measures are attributable to improved efficiencies for implementing improved brick kilns and cleaner burning stoves, which lead to net cost savings, and another 25% to regulatory measures on high-emitting vehicles and banning agricultural waste burning, which require primarily political rather than economic investment, the majority of the BC measures could be implemented with substantially greater benefits than costs.

6.3.3 Conclusions Regarding Potential Health Benefits

All control measures that reduce $PM_{2.5}$ pollution are virtually certain to achieve health benefits. Programs aimed at reducing $PM_{2.5}$ in the United States, such as rules targeting light and heavy duty vehicles, diesel emissions, and marine vessels, as well as industrial stationary sources, have greatly reduced $PM_{2.5}$ concentrations (including BC) and $PM_{2.5}$-related mortality. These programs have very favorable benefit-cost ratios, particularly for the mobile source sector. While progress has been made, the $PM_{2.5}$ health burden in the United States remains significant. EPA has introduced a number of programs for both mobile and stationary sources that are estimated to have a substantial impact on air quality and, as a result, $PM_{2.5}$-related health impacts, over the next several decades. However, additional controls for transportation and stationary sources, as well as for residential wood burning, can further reduce the remaining BC emissions (Chapters 8-11).

The largest opportunities for achieving the health benefits of BC mitigation measures are in lesser developed countries due to high emissions located in densely populated areas, particularly in South and East Asia. Although the body of literature is limited, available studies demonstrate that mitigating BC emissions would have substantial benefits for global public health, potentially avoiding millions of premature deaths each year valued in the trillions of $US. Although valuing health benefits around the world is complicated by data limitations, several studies undertaking such analyses have found that the mortality benefits alone are quite substantial and may alone justify mitigation efforts. Reducing BC emissions from transportation and residential sources, in addition to some BC-rich industrial sources, would likely achieve the greatest combined health and climate benefits. More information on the benefits and costs of individual measures in each country is needed to support policy decisions made at the national level.

6.4 Climate Benefits of Reducing Black Carbon Emissions

A number of recent studies and assessments have pointed to the possibility that reducing BC could provide climate benefits within the next several decades. Some of these studies have focused exclusively on BC, without adequately treating co-emitted pollutants, and/or have estimated direct forcing effects only, without accounting for the potential off-setting cloud interaction effects. As the treatment of BC's atmospheric chemistry and co-pollutants in climate models has advanced, however, studies have begun to focus on certain key sectors and regions as potentially fruitful mitigation options for climate. The recent UNEP/WMO (2011a) assessment, for example, indicates that a small group of carefully targeted BC measures could help improve chances of keeping the Earth's temperature increase to less than 2°C relative to pre-industrial levels (see section 6.4.1). However, the climate benefits of reducing BC emissions are less well understood and less certain than the public health benefits. Because BC concentrations and

[5] The UNEP/WMO Assessment (2011) did not evaluate the full costs of implementing the modeled measures, but did report cost information where available for key demonstration projects in different countries and sectors.

their climate impacts vary spatially and temporally (as discussed in Chapter 2), the location and timing of emissions reductions is critically important for estimating climate benefits of mitigation. In addition, emissions control measures for BC also reduce co-emitted pollutants that lead to cooling (e.g., SO_2, OC). Because many of these co-emitted pollutants lead to climate cooling, the climate benefits of BC emissions control measures may be offset. Therefore, the full mixture of emissions must be considered in estimating the climate benefits of potential mitigation measures. Since these factors are complex and often not well understood, quantitative analysis of the climate benefits of BC mitigation strategies is difficult and the number of related studies is limited.

Of the studies currently available, some have focused on the physical climate benefits of BC mitigation—estimating changes in temperature, ice melt, or radiative forcing. A number of these studies explicitly compare the climate benefits of BC reductions to the climate benefits of reductions in other GHGs. These studies often use metrics such as GWP or GTP (introduced in Chapter 2) as the basis for comparing alternative climate mitigation strategies. Other studies have extended the analysis of climate benefits by attempting to place an economic value on avoided impacts. In a few cases the economic benefits of particular BC mitigation strategies were compared to those of alternative strategies targeting either BC or long-lived GHGs. The next several sections describe (1) the potential physical benefits that can be achieved through BC mitigation, (2) how those benefits compare to benefits that could be achieved through CO_2 mitigation, and (3) the potential value of the climate benefits of BC mitigation.

6.4.1 Studies Estimating Physical Climate Benefits

As discussed in Chapter 2, the nature and distribution of BC and its mechanisms of action mean it can have important direct and indirect effects on climate that differ from those of GHGs. Unlike with GHGs, these effects are not limited to those derived from radiative forcing on a global scale. Rather, the effects associated with BC include alteration of cloud properties, which affects cloud reflectivity, precipitation, and surface dimming. In addition, deposited BC can result in disproportionate warming in areas covered by snow and ice, which is greatest near source regions (e.g. the Himalayas) but still significant in the Arctic.

Most studies on the climate benefits of BC mitigation have focused on estimating the impacts of broad-scale global or regional emissions reductions. Several investigators have used global climate models to examine reductions of BC, OC and in some cases associated GHGs from the fossil, biofuel, and biomass sector sources. Most of these have focused on the effect of global reductions on radiative forcing or temperature. As discussed below, the results generally suggest that the largest climate benefits are likely to accrue from strategies that reduce emissions from BC-rich sectors such as mobile diesel engines and other fossil fuel combustion sources, as opposed to sectors where the quantity of BC compared to co-emitted pollutants is smaller (e.g., biomass burning). Below, we discuss (1) the global climate benefits of BC emissions reductions, (2) benefits of BC reductions specific to ice-covered regions, and (3) key uncertainties in these estimates that are due to insufficient scientific understanding of how aerosols affect climate.

6.4.1.1 Global Climate Benefits of BC Reductions

As discussed previously, some co-emitted pollutants lead to cooling that can counteract the warming by BC. Changes to the entire emissions mixture must therefore be considered when estimating the climate impacts of BC mitigation measures. Several studies have examined the climate impacts of eliminating all emissions from individual sources and found the largest and most consistent benefits in terms of negative forcing (cooling) result from reductions in emissions from fossil fuel sources. For example, Jacobson (2010) found that eliminating all fossil fuel soot reduced surface air temperature by 0.3-0.5 K (13-16% of total net global warming). Another study that evaluated multiple models found that global reductions in open biomass burning (where the emissions mixture typically includes a higher concentration of cooling compounds) produced small but positive climate benefits (Kopp and Mauzerall, 2010).

Several studies have examined the climate benefits of emissions reductions from individual emissions source sectors, again finding that sectors with higher BC ratios generally have larger positive forcing. These studies are generally consistent in finding that transportation and household biofuel combustion contribute more than any other sector to positive forcing. For example, Unger et al. (2010) examined the warming impacts of each major sector's emissions, taking into account the full mixture of aerosols and gases (short-lived and long-lived) from each sector. On-road motor vehicles and household biofuels, major sources of global anthropogenic BC emissions, were found to contribute more than any other sector to globally averaged near-term warming (by 2020) (Figure 6-4). Koch et al. (2007a)

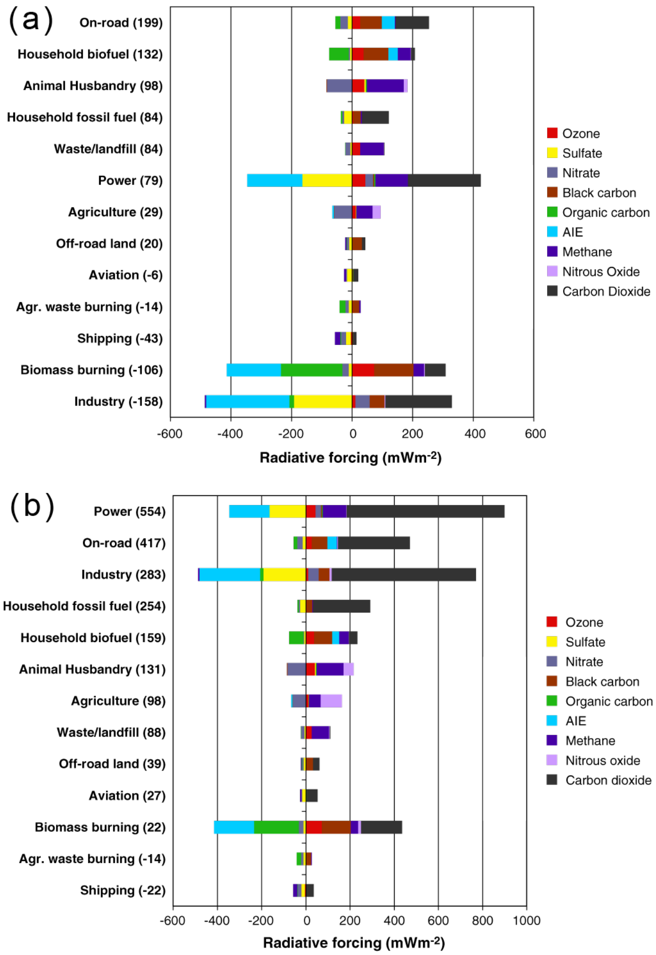


Figure 6-4. Global Radiative Forcing Due to Perpetual Constant Year 2000 Emissions, Grouped by Sector, in 2020 (Top) and 2100 (Bottom) showing contribution from each species. The sum is shown on the title of each bar, with a positive radiative forcing indicating that removal of this emissions source will result in cooling. From Unger et al. (2010) (also shown in Chapter 2).

examined the direct radiative forcing of aerosols only, finding that the sectors that are responsible for the largest BC radiative forcing are residential (0.09 W m^{-2}) and transport (0.06 W m^{-2}), but that co-emitted scattering (i.e., cooling) components reduce these impacts to 0.04 W m^{-2} and 0.03 W m^{-2}, respectively. Shindell et al. (2008a) found that across-the-board emission reductions in household fuel burning in Asia and in transportation in North America are likely to offer the greatest potential for near-term climate benefits. Although these studies were limited to direct radiative effects, Bauer et al. (2010) also found that reducing diesel emissions would reduce positive forcing (i.e., warming) even when accounting for cloud changes, which can result in cooling. In another study examining the effects of all aerosols, Bauer and Menon (2012) reached similar conclusions. This study focused on regional differences in the impact of emissions from different source categories, and concluded that the largest opportunities to reduce positive forcing due to all aerosols included transportation in all regions, agricultural burning in Europe and Asia, and residential cooking and heating ("domestic sector") in Asia.

This body of literature suggests that both transportation and residential BC sources may be attractive targets for BC mitigation measures. Although several of these studies found that reductions in industrial and power generation emissions may accelerate near-term warming (Unger et al., 2009; Shindell et al., 2008a), this broad categorization includes a variety of different types of sources, some of which are major emitters of SO_2, a precursor of sulfate (a "cooling" aerosol). Within the industrial sector, however, are some sources (e.g., brick kilns, coke ovens) that are major emitters of BC in the developing world. Controlling emissions from these specific BC-rich sources will likely also lead to climate benefits, as discussed below. As with any strategy development, determining the specific optimal measures to implement depends on a number of factors in addition to the climate and public health benefits. These factors are discussed in more detail in Chapter 7.

Several recent studies have examined how specific emission control measures are expected to reduce emissions. To date, the most comprehensive assessment of this type is the UNEP/WMO Assessment described in Section 6.3.2 (UNEP and WMO, 2011a; Shindell et al., 2012). This study found that implementing an illustrative set of BC and methane (CH_4) emission control measures together would reduce future global warming by 0.5°C (0.2°C - 0.7°C), with about half the reduction specifically from the BC measures. Implementing the BC and CH_4 emission control measures by 2030 was estimated to halve the expected increase in temperatures for 2050 compared with the reference scenario (based on current policies and energy and fuel projections), as shown in Figure 6-5. This study used a range of values from the literature reflecting the indirect and direct radiative forcing effects of BC and OC to provide a range of expected outcomes that account for uncertainty. A follow-on study to the UNEP/WMO Assessment found that the measure likely to produce the greatest near-term global climate benefit is switching from traditional biomass cookstoves to cleaner burning stoves, followed by reducing emissions from the transportation sector (UNEP, 2011).

Because transportation emissions are expected to contribute the most to BC-related warming in the future (Koch et al., 2007b), Shindell et al. (2011) examined the climate benefits of imposing tighter vehicle emission standards in China, India, Africa, the Middle East, and Latin America. Relative to no additional controls, imposing these standards led to significant reduction in warming in the Northern Hemisphere extra-tropical region (reduction of 0.22°C, with a potential range from 0.04°C to 0.38°C) and in the Arctic (reduction of 0.28°C, with a potential range from 0.02°C to 0.47°C) over the next 50 years, although the total reduction in global warming after 2040 overall was small. Controlling emissions from heavy-duty diesel trucks in India and Brazil was found to have the greatest climate benefits, followed by controls on medium-duty diesel vehicles in India and light-duty petrol vehicles in North Africa and the Middle East. Controlling emissions from light-duty gasoline vehicles everywhere and from motorcycles and medium-duty trucks in some regions also provides climate benefits that are more limited. These BC reductions were also associated with precipitation changes, but such results are highly uncertain and warrant further study. Despite large uncertainties, this study demonstrates the substantial climate benefits of controlling emissions from the motor vehicle sector around the world.

Few studies have examined the climate benefits of specific particle control programs on smaller, more localized scales. A recent study of particular relevance examined the results from California's laws to reduce particle pollution, in particular those regulating diesel emissions. The study found that these rules reduced atmospheric concentrations of BC with a measurable impact on regional radiative forcing. Modeled results indicate that the decrease in BC emissions in California has led to a cooling

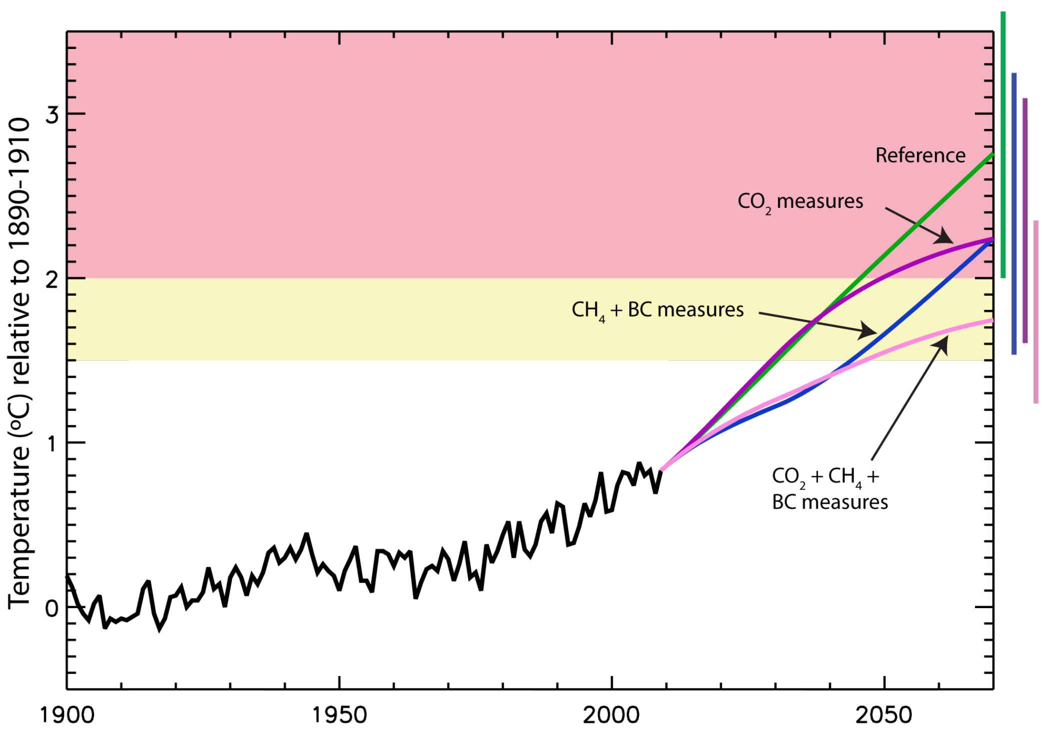


Figure 6-5. Observed Deviation of Temperature to 2009 and Projections under Various Scenarios. Immediate implementation of the identified BC and CH_4 measures, together with measures to reduce CO_2 emissions, would greatly improve the chances of keeping the Earth's temperature increase to less than 2°C relative to pre-industrial levels. The bulk of the benefits of CH_4 and BC measures are realized by 2040. (UNEP and WMO, 2011a)

Note: Actual mean temperature observations through 2009, and projected under various scenarios thereafter, are shown relative to the 1890–1910 mean temperature. Estimated ranges for 2070 are shown in the bars on the right. A portion of the uncertainty is common to all scenarios, so that overlapping ranges do not mean there is no difference. For example, if climate sensitivity is large, it is large regardless of the scenario, so temperatures in all scenarios would be towards the high end of their ranges.

of 1.4 W m^{-2} (±60%) (Bahadur et al., 2011). So, while uncertainties remain, as outlined in previous chapters, emerging research suggests that targeting emissions reductions from key sectors can have measurable benefits for climate.

6.4.1.2 Benefits of BC Reductions on Snow- and Ice-Covered Regions

As noted above, BCs effects are highly regionalized and include impacts on precipitation, atmospheric stability, and snow/ice melting that differ in important ways from those driven by GHGs. Global modeling provides useful insights into potential responses in regions identified in Chapter 2 as being particularly affected by BC emissions. For example, Jacobson (2010) found the extreme strategy of eliminating all anthropogenic emissions from sources of fossil fuel and biofuel BC would reduce global temperatures by 0.4 to 0.7° C; with a reduction of about 1.7° C in the Arctic. This is consistent with other modeling and analysis discussed in Chapter 2 that suggest a larger impact of BC and other pollutants on the Arctic, and thus greater potential benefits from emissions control measures.

Recent findings of the Arctic Council Task Force on Short-Lived Climate Forcers suggest that mitigating sources of BC emissions in or near the Arctic will have greater climate benefits in that region, with important seasonal and spatial variations. Impacts in the Arctic are greatest during the spring and summer months when the solar radiation is the strongest. Specifically, in its 2011 *Progress Report and Recommendations for Ministers* (Arctic Council, 2011), the Task Force noted that:

> *[I]n the Arctic, the potential for … offsetting effects from non-black carbon aerosols is weaker. Over highly reflective surfaces such as ice and snow in the Arctic, the same substances that might cool the climate in other regions may cause warming since they are still darker than ice and snow. This warming impact is magnified when black carbon physically deposits on snow or ice. Emissions closer to the Arctic have a greater chance of depositing, and thus appear to have greater impact per unit of emission.*

The Task Force highlighted the importance of reducing emissions from in-Arctic sectors such as land-based transportation, open biomass burning, residential heating, and marine shipping in the Arctic, but also noted that emissions from outside the Arctic, especially those in close proximity to the Arctic, are important for Arctic climate change, partly because of the volume of these emissions and (as noted above) because of the relatively small cooling effect of co-emitted pollutants in the region.

The 2011 Arctic Monitoring and Assessment Programme (AMAP) report, "The Impact of Black Carbon on the Arctic" examined the influence of BC emitted from different sources and world regions on radiative forcing and temperature in the Arctic (Quinn et al., 2011). This study found that in general, BC *deposition* on snow and ice in the Arctic (which contributes to the snow/ice albedo effect described in section 2.6) exerts a greater warming effect than within-Arctic direct radiative forcing from BC in the atmosphere. Furthermore, both direct forcing and snow/ice albedo forcing in the Arctic *per unit of emissions* were shown to be highest for emissions originating near to or within the Arctic region, with

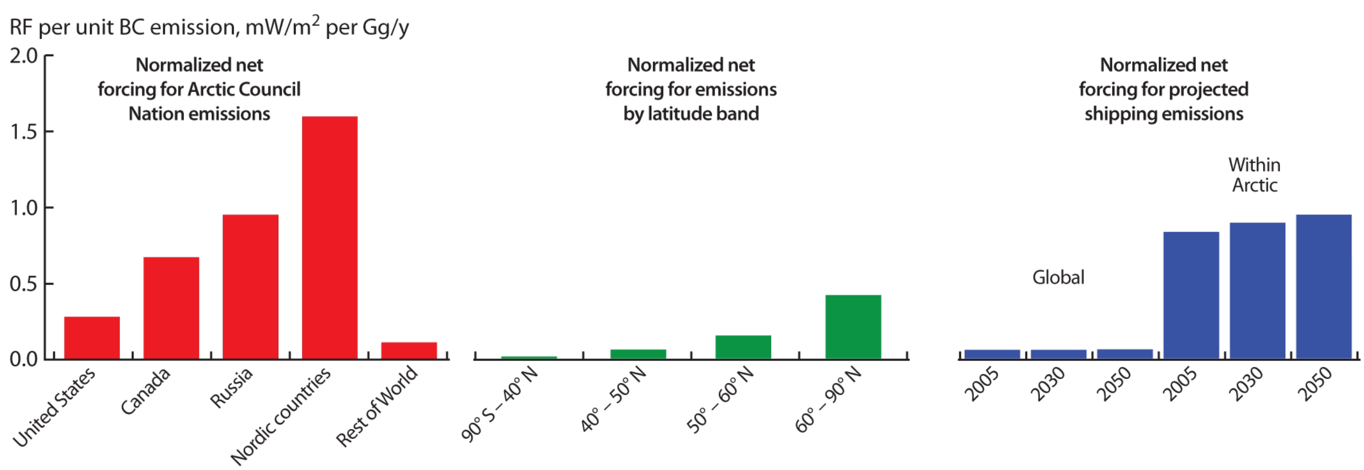


Figure 6-6. Summary of Normalized Net Forcing per Unit of Emissions (includes atmospheric direct forcing by BC and BC-snow/ice forcing) due to emissions from Arctic Council nations and the rest of the world, the indicated latitude bands, and global and within-Arctic shipping. (Source: Quinn et al., 2011)

the Nordic countries (i.e., highest latitudes) having the highest forcings per unit of emissions, followed by Russia, Canada, and the United States (Quinn et al., 2011, p. 95). These impacts are illustrated in Figure 6-6. This is because within-Arctic BC sources are more likely to cause warming near the surface and to lead to BC deposition on snow and ice surfaces. Furthermore, warming at high altitudes reduces atmospheric energy transport into the Arctic; as a result, AMAP (Quinn et al., 2011) found that direct atmospheric forcing by BC that has been transported into the Arctic at high altitudes may have a relatively small impact on Arctic surface temperatures.

However, the Arctic climate is coupled with that of the Northern Hemisphere and is thus sensitive to changes in radiative forcings in other nearby regions. Since the bulk of global BC emissions occur outside the Arctic, and since global BC forcing results in poleward transfer of heat energy, Arctic temperatures are significantly affected by BC direct forcing occurring outside the Arctic region. Overall, when total global emissions are considered, BC emissions in the rest of the world are the dominant influence on radiative forcing in the Arctic (Figure 6-7). The AMAP results confirm both that latitude and the total magnitude of emissions matter:

> *It has been suggested that emissions north of 40°N have a large impact on the Arctic particularly in the winter and spring when the polar dome extends to the mid-latitudes over Europe and Asia .... To test this assumption and to compare the potential impact of sources on Arctic climate as a function of latitude between 40°N and 90°N, a set of experiments was performed with emissions gridded by latitude band. The latitude bands included in the analysis were 90°S to 40°N, 40°N to 50°N, 50°N to 60°N, and 60°N to 90°N. ... [E]missions in the most southerly latitude band (90°S to 40°N) result in the largest direct RF due to the magnitude of the emissions of BC in the northern hemisphere tropics and mid-latitudes. Atmospheric direct RF also is relatively large for the 40°N to 60°N latitude band because of the magnitude of emissions and likelihood of transport to the Arctic. Emissions within the Arctic (60°N to 90°N) result in a smaller absolute direct RF because of their lower magnitude compared to emissions in more southerly latitude bands. Absolute BC-snow/ice RF increases with latitude between 40°N and 60°N. This result confirms that emissions from lower latitudes are less effectively deposited in the Arctic since they reach the Arctic at higher altitudes .... Normalized BC-snow/ice RF increases dramatically with increasing latitude band ... confirming the efficiency with which sources close to the Arctic are transported to and deposited within the Arctic. This result also indicates that per unit emission, sources within the Arctic yield the largest RF. (Quinn et al., 2011, p. 57)*

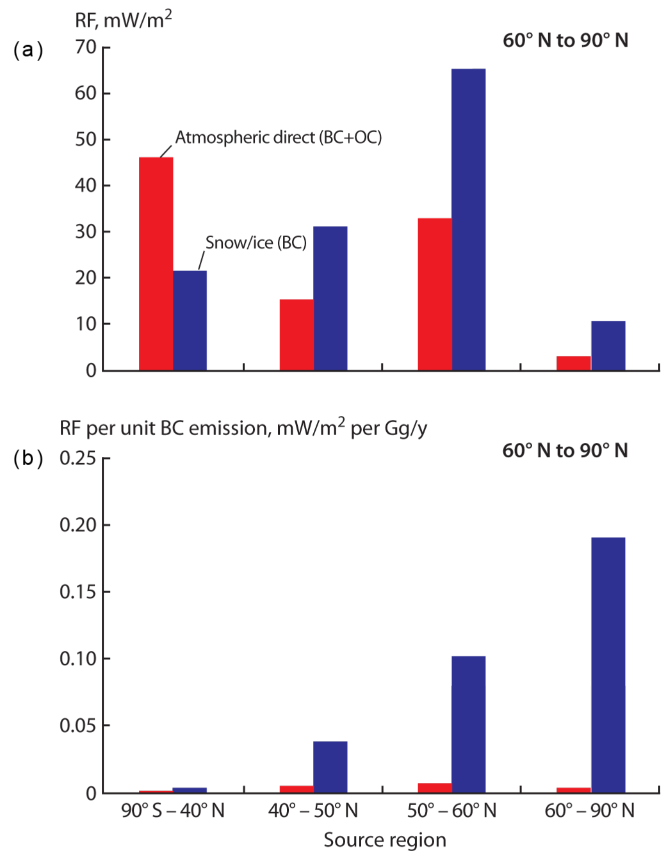


Figure 6-7. Contribution to Radiative Forcing of Carbonaceous Aerosol Emissions within Different Latitude Bands. (a) Absolute and (b) Normalized per unit emission atmospheric direct radiative forcing due to BC+OC and BC-snow/ice radiative forcing as a function of latitude band. (Quinn et al., 2011, Figure 8-9)

Importantly, AMAP (Quinn et al., 2011) indicates that reductions in OC emissions will provide benefits in the Arctic too, since OC emissions appear to exert positive radiative forcing over snow- and ice-covered surfaces. Note that the radiative forcings reported in Figure 6-7 are for the combination of OC+BC emissions. Similarly, sulfate aerosols, which normally exert a cooling influence, appear to have a much weaker cooling effect over snow and ice (Quinn et al., 2011). While aerosol indirect forcing effects in the Arctic are highly uncertain, current evidence suggests that indirect and semi-direct effects are less negative in the Arctic than for the global average. This all means that a wide array of measures aimed at reducing BC and OC in or near the Arctic will provide benefits to the Arctic region, as will BC-focused strategies elsewhere. AMAP (Quinn et al., 2011) concluded that global strategies to manage BC emissions are necessary to mitigate Arctic climate change.

There is relatively less information regarding specific benefits of BC reductions for other snow- and ice-covered regions, including the Himalayas. As discussed in section 2.6.5, Menon et al. (2010) modeled the impacts of estimated increases in BC between 1990 and 2000 and found that in particular BC from fossil fuel/biofuel use in India may be responsible for some of the observed patterns and trends in snow and ice melting and precipitation in the Himalayan region. Such changes may have significant implications for water supply in the region. While a number of studies have suggested BC and associated emissions may play a role in reduced monsoon rains, current modeling capabilities do not provide a basis for reliable quantitative assessments of the extent to which emissions reductions might reverse observed changes in precipitation.

6.4.1.3 Key Uncertainties in Estimating Climate Benefits of BC Reductions

As discussed in detail in Chapter 2, the results from the studies described in the previous subsections have some level of uncertainty. The primary sources of this uncertainty include lack of understanding about:

- The climate effects of reductions in co-emitted pollutants, especially brown carbon (BrC) emissions and the extent to which they contribute to radiation absorption (Magi, 2009).
- The effect of model representation of aerosol mixing state and aerosol-cloud interactions, including radiative effects and precipitation effects, on estimated climate impacts. These processes can have a major influence on the overall warming or cooling effect of emissions changes.
- Effects of non-BC aerosols in the Arctic.
- Effects of other atmospheric processes (such as atmospheric transport and deposition) on climate outcomes.

In addition, errors in the emissions inventories of BC and OC and other reflecting agents from each sector, particularly for residential solid fuel combustion, may lead to over or under estimation of the magnitude of the climate impact.

6.4.2 Comparing Climate Benefits of Reductions in BC vs. CO_2

While studies performed to date do not include the full set of aerosol interaction effects, co-emissions, or other uncertainties, taken as a whole they suggest that reductions of BC may be among the most effective strategies for reducing near-term warming, and can *complement* GHG reductions as part of an overall climate strategy (Grieshop et al., 2009; Kopp and Mauzerall, 2010). As described in Chapter 2, BC reductions can reduce the rate of climate change and provide climate benefits in the near term. However, BC reductions today have much smaller effects on temperatures in 100 years. Therefore, BC emissions reductions cannot *substitute* for CO_2 reductions for purposes of alleviating long-term warming. Studies indicate that BC emissions reductions that come at the expense of reductions in CO_2 emissions would result in short-term cooling but add an additional commitment to long-term radiative forcing due to the life time of CO_2 in the atmosphere (Lack et al., 2009).

The UNEP/WMO BC and Tropospheric Ozone Assessment (UNEP and WMO, 2011a) described in sections 6.3.2 and 6.4.1 compared the climate benefits of groups of BC and CH_4 mitigation measures to a scenario developed by the International Energy Agency in which long-lived GHG concentrations were reduced to a level of 450 ppm CO_2eq (International Energy Agency, 2009). As illustrated by Figure 6-5, the reductions in CH_4 and BC combine to produce a noticeable impact on near-term warming as compared to the reference case or CO_2 measures by themselves. The analysis showed that even aggressive CO_2 reductions may not keep climate change from approaching 2°C by mid-century.[6] At the same time, it is important to note that the benefits of reducing BC and CH_4 are insufficient to avert warming over the long term. Reducing short-lived climate forcers now, while neglecting to achieve aggressive CO_2 reductions, may not keep temperatures from reaching the 2°C mark in 2070 and beyond. These results, and those from other studies on the temporal aspects of reducing BC and other short-lived forcers, underscore the scientific rationale for reducing long-lived GHGs and BC simultaneously as two distinct, complementary strategies that act on different time scales to address global warming and other effects of climate change.

[6] An increase in global mean temperatures of 2°C since preindustrial times was adopted as an international target under the UN's Copenhagen Accord in December 2009.

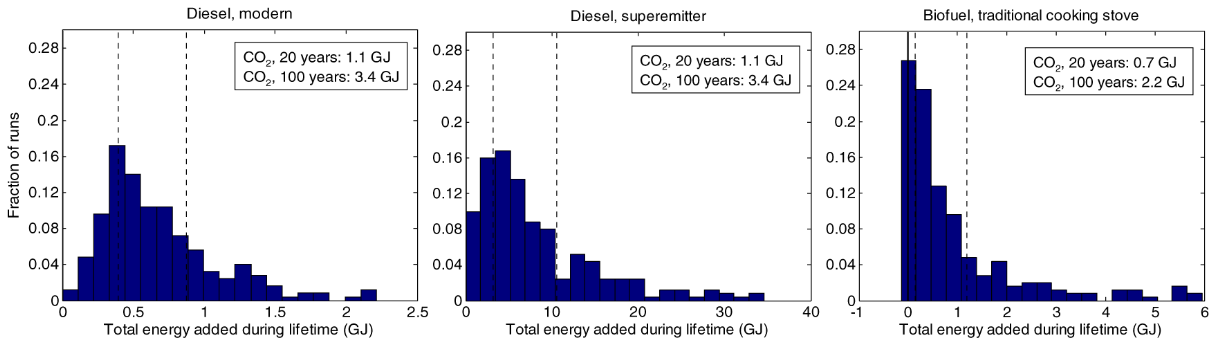


Figure 6-8. Integrated Forcing by Aerosols Emitted from Burning 1 Kg of Fuel from Different Sources, based on results of 250 Monte Carlo simulations. (Note scale differences.) (Bond, 2007, Figure 6)

Among the other studies comparing BC and CO_2 strategies, Grieshop et al. (2009) used a valuation that "one ton of black carbon causes about 600 times the warming of one ton of carbon dioxide over a period of 100 years" to state that eliminating present-day emissions of BC over the next 50 years would have "an approximately equivalent climate mitigation effect to removing 25 Gt C from the atmosphere over the same period."[7]

Some studies also account for changes in co-emissions from BC and GHGs that may affect climate outcomes. For BC, the co-emissions (e.g. SO_2, OC) are often reduced by the same control measures that affect BC and the climate impacts are generally realized on the same timescale as (i.e., short atmospheric lifetimes lead to near-term climate effects). For CO_2, there is a gap between climate effects due to CO_2 and effects due to co-emitted species, since the latter generally have a shorter lifetime. Furthermore, with CO_2, it is often possible to reduce co-emissions separately with end-of-pipe technologies, which makes it possible to make independent decisions about how much to reduce CO_2 vs. co-emissions from a given source. All of this illustrates the importance of accounting for co-emissions in climate models, but also the complexity of assessing the impact of specific control measures.

Other studies have indicated that implementing aerosol mitigation measures for BC-rich sources can yield more cooling over the short term (10-20 years) than eliminating CO_2 emissions from those sources (Bond, 2007; Jacobson, 2005; Sarofim, 2010). Sarofim (2010), for example, addressed one specific mitigation option (retrofits of some U.S. diesel vehicles) and showed that the CO_2 equivalent reductions calculated by using a GWP would lead to radiative forcing reduction from black carbon mitigation peaking in the year that the vehicles are retrofitted and dropping to almost zero change in global radiative forcing after 20 years as the retrofitted vehicles are retired. In contrast, the radiative forcing reduction from the CO_2 equivalent mitigation calculated using GWPs peaks about a decade after the start of the mitigation period at only a tenth of the BC peak, but at the end of the century the radiative forcing reduction is still more than half of what it was at that peak.

Bond (2007) examined emissions from multiple source types and compared the total radiative (integrated) forcing from those sources over 20 years for carbonaceous aerosols (both OC and BC) to the integrated forcing from CO_2 (an approach similar conceptually to using GWP weightings). The study showed that the aerosol emissions resulting from burning 1 kg of fuel in a super-emitting diesel vehicle has more than a 90% chance of contributing more total forcing than CO_2 from that source over a 20 year timeframe, and even for a normal (pre-2007) diesel, the aerosol emissions resulting from burning 1 kg of fuel are likely to contribute more than half as much warming as the CO_2 emissions over 20 years (see Figure 6-8). This study did not account for the indirect effects of aerosols or snow albedo effects. Jacobson (2005) did include co-emissions and more cloud interactions, and still found that diesel vehicles warmed climate more than gasoline vehicles for 13-54 years, because the higher BC emissions from diesel vehicles outweighed the lower CO_2 emissions over that timeframe.

A different approach avoids the limitations of choosing a single metric to compare emissions of

[7] In this study, 25 Gt was chosen because it equals one "wedge" from the Pacala and Socolow (2004) study that identified large-scale mitigation options over the next 50 years. However, Grieshop et al. (2009) did not involve any calculations to compare the short-term and long-term effects of implementing a BC wedge rather than an additional greenhouse gas wedge, did not examine co-emissions, and did not take into account cloud interaction effects.

BC and CO_2, and instead investigates how reductions of BC over the entire century would change the difficulty of meeting radiative forcing targets. Kopp and Mauzerall (2010) calculated the optimal CO_2 emissions pathways in order to meet a 2.21 W m^{-2} target in 2100. Rather than assessing the benefits of BC reductions in the near future like the previous studies, this study assessed the radiative benefits of BC reductions at the end of the century and then translated those benefits into near term CO_2 emissions targets. This study included both co-emissions and an estimate of indirect effects. They found that meeting this target required 50% reductions of CO_2 by about 2050. However, if this target were tightened to accommodate the positive radiative forcing from carbonaceous aerosols (both OC and BC) from contained combustion source (fossil fuels and biofuels), then the 50% reduction of CO_2 would need to occur 1 to 15 years earlier, depending on the assumptions about carbonaceous aerosol emissions pathways and forcing strength.

6.4.3 Valuing the Climate Benefits of BC Mitigation

Another way to evaluate the benefits of BC mitigation strategies and to compare them with the benefits of other climate mitigation strategies is to use valuation techniques to create monetary estimates of avoided damages. This would be equivalent to the approach adopted to compare the health benefits of different regulatory approaches discussed above in section 6.3. However, methods for establishing the economic value of the climate damages associated with BC are still being developed. Two metrics, the Global Damage Potential (GDP) and the social cost of a pollutant, involve monetization of the damages of climate change. Assessing the value of damages through a single metric (i.e., dollars) provides useful information that can help inform policymakers regarding the scale and scope of the climate impacts of BC and the benefits that can be gained from BC mitigation. However, no study to date has fully monetized the climate impacts of BC. An analysis of this type would need to include the benefit of avoiding risks and impacts associated with warming (especially near term warming and rate of change),as well as the value of avoiding impacts such as accelerated ice and snow melt and changes in precipitation induced by BC.

Currently, efforts to develop valuation methods for climate impacts have focused on CO_2. In computing the value to society of avoided climate damages, EPA assigns a benefits dollar value to CO_2 emission reductions using estimates of a "social cost of carbon" (SCC) developed by a U.S. federal government interagency working group in 2010. The SCC is an estimate of the monetized damages resulting from an incremental increase in CO_2 emissions in a given year; likewise, it can be thought of as the monetized benefit to society of reducing one ton of CO_2. The SCC estimates are intended to include an array of human-induced climate change impacts, such as changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. Current SCC values, such as those utilized by EPA to analyze the benefits of the 2010 *Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards* (U.S. EPA, 2010c), are subject to a number of limitations, including the incomplete way in which the underlying climate models capture catastrophic and non-catastrophic impacts, the incomplete treatment of adaptation and technological change, uncertainty in the extrapolation of damages to high temperatures, and assumptions regarding risk aversion. The SCC estimates developed for CO_2 have been controversial due to the difficulty of estimating economic impacts across nearly every sector of the economy as well as valuation issues regarding impacts on natural ecosystems. Furthermore, these estimates were developed exclusively for CO_2 and are not directly transferrable to other GHGs or BC.[8]

It might be possible to use a similar approach to develop a social cost specific to BC using integrated assessment models (IAMs) that combine economic growth, climate processes, and feedbacks between the global economy and climate into a single framework to translate BC emissions into economic

[8] One approach that might appear tempting is to use existing estimates for the SCC for CO_2, and translate them into a social cost for BC using metrics such as the 100-year global warming potential, or GWP (see, for example, Copenhagen Consensus Center Reports). However, the damage functions used in the underlying models are sensitive to when and by how much the temperature changes – therefore, given the orders of magnitude shorter lifetime, a social cost calculated from first principles for BC could be very different than one that merely scales the social cost of CO_2 by the GWP. Again, regional dependence and impacts on precipitation patterns would not be captured by this method, nor would the regional dependence of snow and ice deposition and therefore special sensitivity of alpine and Arctic ecosystems to BC emissions. Therefore, the social cost of BC might not be well represented by using GWPs to scale an SCC. (See further discussion of the applicability of GWP metrics to BC in Chapter 2.) Given that warming profiles and impacts other than temperature change vary across climate forcers, the interagency SCC working group made a preliminary conclusion that transforming other climate forcers "into CO_2-equivalents using global warming potential, and then multiplying the carbon-equivalents by the SCC, would not result in accurate estimates of the social costs" of these non-CO_2 forcers (Interagency SCC Group, 2010), though it is unclear how large such an error would be.

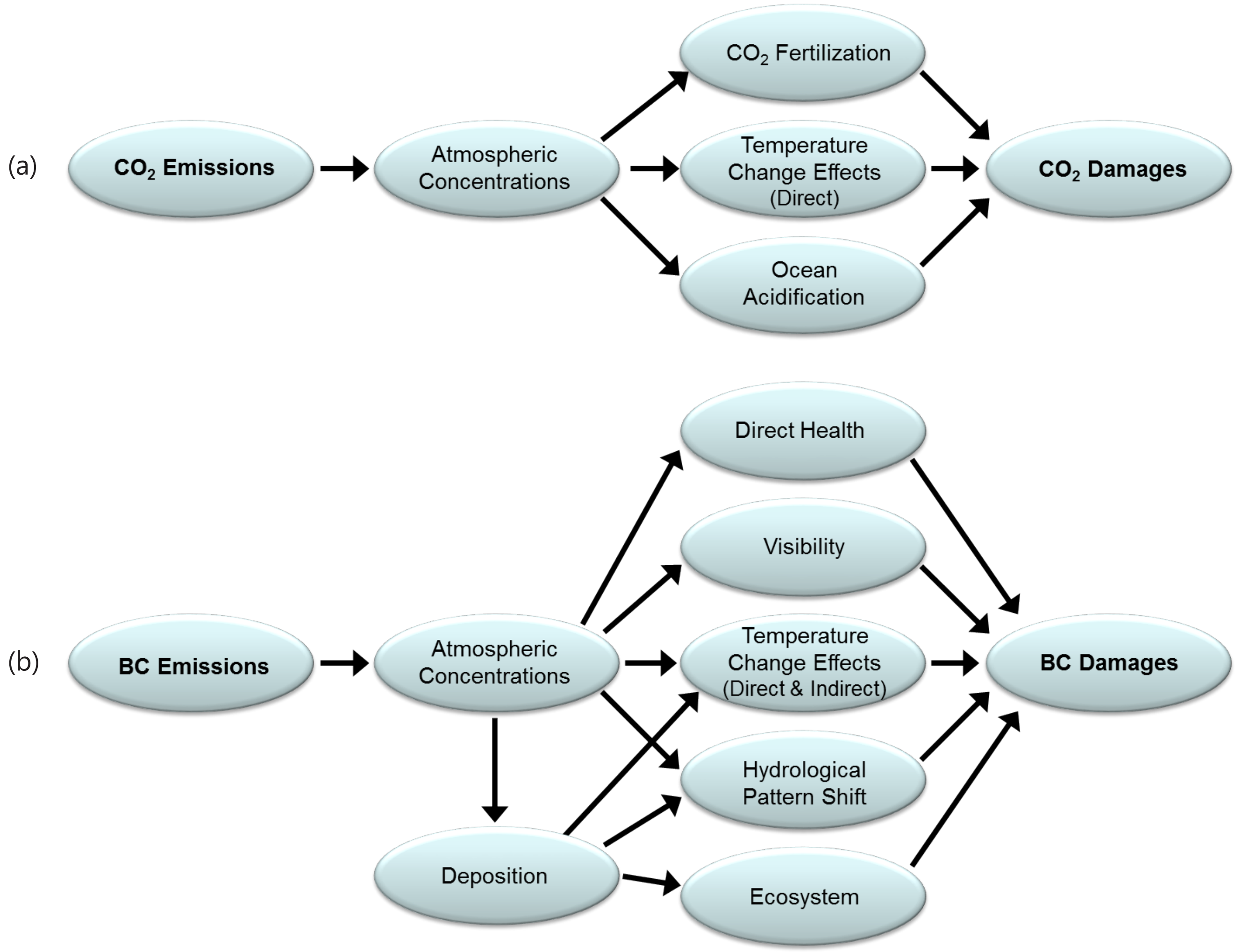


Figure 6-9. Cause and Effect Chains for (a) CO_2 and (b) BC from Emissions to Damages. (Source: U.S. EPA)

damages. However, there are a number of factors that would complicate these calculations. These difficulties stem partly from limitations in the capabilities of IAMs, and partly from the complexity of the cause-effect chain needed to measure the physical links between emissions and climate change impacts, and to calculate damages (see Figure 6-9).

Few IAMs are designed to demonstrate regional impacts, and currently these models do not adequately consider the impact of BC and other short-lived climate forcers on the *rate* of climate change. In addition, the feasibility of considering indirect climate effects such as the impact of BC on snow and glacier melt and changes in precipitation patterns in the IAMs must be evaluated. In one aspect, at least, calculating a social cost for BC might actually be easier than calculating a social cost for CO_2: the short lifetime of BC and the relatively immediate nature of the climate impacts reduce the extent to which social cost calculations would depend on the social discount rate selected. Due to the complexities involved with valuing the climate benefits of BC reductions, a top-down approach using IAMs may not be preferred. Rather, a bottom-up approach that considers location, emission profiles of sources, and ambient concentrations and deposition of BC similar to the approaches used to quantify health effects may be needed.

The cause-effect chain from emissions to impacts and damages is also complex for BC. The regional nature of many BC impacts, the importance of location of emissions, and BC's impacts on precipitation, snow/ice, and surface dimming add additional complexities to any such approach that are not present for CO_2 SCC calculations. In addition, the peer reviewed literature lacks impact functions and valuation methods necessary to assess many of these BC effects. Finally, because BC is emitted as part of a mixture, incorporation of the climate impacts of reducing other co-emitted aerosols into a social cost approach would reflect the net impact more accurately.

The Global Damage Potential (GDP) compares the relative damage resulting from an equal mass of emissions of two climate forcers (IPCC, 2009) – effectively, the ratio of the social cost of a climate forcer to the social cost of carbon. The GDP is meant to be a parallel approach to the GWP, and therefore might potentially be calculated using some of the same assumptions that go into the GWP calculation. One key assumption is that the background concentration is a constant, modified only by the initial pulse of emissions. This simplifies the calculation of the GWP or GDP because it requires no assumptions about a reference emissions pathway. However, because the impact of increased concentrations depends on the starting concentration, this simplification means that the metric may not accurately reflect actual damages.

As this discussion of GDP and SCC illustrates, calculating economic damages associated with specific climate forcers is extremely complicated. Even where risks and impacts can be identified and/or quantified with physical metrics, it may be difficult to monetize these risks and impacts (e.g., such as ecosystem damage or the potential to increase the probability of an extreme weather event) such that an accurate cost-benefit comparison could be undertaken. Both the GDP and the social cost calculation depend on the physical aspects of the climate system as well as the economic linkages between climate change impacts and the economy (IPCC, 2009). Therefore, the GDP and the social cost require calculations of the entire cause and effect chain, but as a result contain a large amount of uncertainty. Additional work is needed to design approaches to valuing climate impacts of BC directly, and to incorporate those approaches into metrics comparable to the SCC.

Some authors have attempted to incorporate economic valuation approaches into a comparative framework that enables direct comparisons between the benefits of BC mitigation and the benefits of CO_2 mitigation. If fully developed, such approaches could be utilized to help policymakers choose among an array of mitigation choices involving different pollutants, different sources, and different timeframes. Using a computer model that included economic considerations, Manne and Richels (2001) examined relative tradeoffs between different gases that vary over time and are calculated to optimally achieve a given target. The paper demonstrated that if a long-term temperature stabilization target is the only policy goal, then reductions of short-lived gases have little value compared to long-lived gases as long as the target will not be reached for several decades, but that the value of these short-lived gases rises rapidly as the temperature approaches the target. Manne and Richels also examined a case in which the rate of change of temperature was a goal along with the long-term temperature change, finding that in that case the relative prices of the different gases stay more constant over time. This kind of approach, including economic considerations for cost of control but without looking at the benefits of those controls, is known as a cost-effectiveness analysis. The relative tradeoff between a given gas and CO_2 is also known as the Global Cost Potential (GCP).

6.4.4 Conclusions Regarding Climate Benefits

The climate benefits of BC mitigation are less well understood and less certain than the health benefits. Studies examining across-the-board emissions reductions from individual sectors find that the warming impact of source sectors generally corresponds with the OC/BC ratio of that sector, with the benefits from source sectors that have low OC/BC ratios (e.g., fossil fuel-based sectors) being higher.[9] Most studies are consistent in finding that the transportation sector contributes the most to positive radiative forcing, followed by household biofuels. Industrial sources are often found to have a net cooling impact; however, this broad categorization neglects to highlight several sub-sector sources that are major BC emitters, including brick kilns and coke ovens in developing countries. The magnitude of the results from studies estimating the climate benefits of emissions reductions are often uncertain due to uncertainty regarding co-emitted species, indirect effects, and effects on precipitation. However, the studies described above demonstrate that several specific and presently available emissions control measures are likely to have substantial climate benefits. These include emissions control measures for vehicles, residential burning of solid fuel, and major industrial sources of BC including brick kilns and coke ovens. The available literature also strongly suggests that BC mitigation can provide particular benefits to sensitive regions, including the Arctic and the Himalayas. These regions stand to benefit disproportionately from reductions in BC, especially if reductions can be achieved from sources within the regions themselves.

[9] Bond et al. (2011) found that for direct forcing only, a ratio of about 15:1 for OC to BC is close to climate neutral.

Comparing the climate benefits of BC and CO_2 mitigation is complicated by the many differences in lifetime and mechanisms of impact between these climate forcers. BC reductions can reduce the rate of climate change and provide climate benefits in the near term, but cannot *substitute* for CO_2 reductions for purposes of alleviating long-term warming. Thus, controlling both short-lived forcers and long-lived greenhouse gases is necessary to achieve the target of constraining temperature rise to no more than 2°C as agreed upon by the international community.

Several metrics have been suggested to value the climate benefits of BC mitigation in economic terms. Assessing the value of damages through a single metric (i.e., dollars) provides useful information that can help inform policymakers regarding the scale and scope of the climate impacts of BC and the benefits that can be gained from BC mitigation. However, no study to date has fully monetized the climate impacts of BC, and a great deal of additional work is needed to design approaches for doing so.

6.5 Environmental Benefits of BC Reductions

In addition to health and climate benefits, there are additional environmental benefits related to reductions in $PM_{2.5}$ including BC. While EPA has had some success in quantifying and valuing benefits from improved visibility, other important impacts such as ecosystem effects and damage to building materials are not easily quantified. In general, however, the environmental benefits of reducing $PM_{2.5}$ have been shown to be quite large in the United States. Importantly, the majority of environmental benefits globally are likely to accrue to other countries, i.e., those investing in emission reduction programs. This is particularly true for those areas where ambient $PM_{2.5}$ is interfering with rainfall patterns (discussed above, in the section on climate impacts) or causing surface dimming on a broad scale. The next sections describe what is known about how $PM_{2.5}$ reductions can (1) improve visibility, (2) reduce pollutant impacts on ecosystems, and (3) enhance the longevity of building materials.

6.5.1 Visibility Impacts

Visibility impairment is caused by the scattering and absorption of light by suspended particles and gases in the atmosphere. A number of other factors can influence visibility, such as the relative atmospheric humidity, intensity of sunlight, presence of cloud cover, distance from the object being viewed, physical characteristics of the object being viewed, and physical capabilities (i.e., eyesight) of the viewer (Malm, 1999). However, when $PM_{2.5}$ is present in the air, its contribution to visibility impairment typically greatly exceeds that of naturally occurring atmospheric gases (U.S. EPA, 2011d). As a result, in otherwise constant conditions, visibility impairment is greater when PM is present. Reductions in air pollution from implementation of various programs associated with the Clean Air Act (CAA) Amendments of 1990 provisions have resulted in substantial improvements in visibility, and will continue to do so in the future.

Visibility directly affects people's enjoyment in a variety of daily activities and their overall sense of well-being. Individuals value visibility both in the places they live and work, in the places they travel to for recreational purposes, and at sites of unique public value, such as national parks. Visibility economic benefits consist of the aesthetic benefits of better visibility, improved road and air safety, and enhanced recreational activities like hunting and bird watching. As with health benefits, visibility improvements are valued using WTP studies. EPA estimates that in 2010, improvements in visibility related to the 1990 CAA Amendments were valued at approximately $36 billion annually (2010$) (U.S. EPA, 2011c). Almost three-quarters of these benefits ($27 million) result from residential visibility improvements. It is important to note that residential benefits in this EPA study reflect benefits from all metropolitan statistical areas in the country, whereas recreational benefits are limited to visibility improvements in Class I areas managed by the National Park Service in California, the Southeast and Southwest.

6.5.2 Ecosystem Impacts

Ecosystems perform a number of functions that contribute to human welfare, including the provision of food and raw materials, filtering of air and water, and protection from natural hazards such as floods (U.S. EPA, 2011d). Additionally, people may seek out certain ecosystems for their aesthetic value. Atmospheric $PM_{2.5}$ negatively affects the ability of ecosystems to perform these and other valuable welfare functions. $PM_{2.5}$ can impact ecosystems through direct deposition on plants, animals, or bodies of water. In areas with high emissions, $PM_{2.5}$ deposition on leaves interferes with a plant's ability to perform basic metabolic functions. Increases in trace metal and organic matter in bodies of water as the result of $PM_{2.5}$ deposition are toxic for aquatic life forms (U.S. EPA, 2009b). Indirect impacts are caused when plants and animals take in pollutants through affected soil or water. As with direct impacts, indirect impacts can alter normal biological processes and be toxic to living organisms.

The relationship between $PM_{2.5}$ and ecosystem effects is difficult to quantify because of the variability in $PM_{2.5}$ emissions and composition. Pollutants accumulate over time in affected organisms, making it difficult to link impacts to ambient $PM_{2.5}$ concentrations. Additionally, the impact of negative welfare effects may vary based with geographic location. The impact of damage to a national park would likely be valued differently than damage to commercial farm land, which would in turn be valued differently than damage to private non-commercial property (U.S. EPA, 2011d).

6.5.3 Materials Co-benefits

$PM_{2.5}$ deposition on materials such as stone, metal, and painted surfaces leads to damage by accelerating the natural weathering process. Chemical reactions with acidic gases worsen the impact of $PM_{2.5}$ -related damage. Additionally, accumulation of $PM_{2.5}$ on surfaces, referred to as soiling, affects the aesthetic properties of materials and necessitates more frequent cleaning or repainting of affected surfaces. Research has not established any quantitative relationship between the ambient concentrations of $PM_{2.5}$ and the rate of damage or soiling caused by $PM_{2.5}$ deposition (U.S. EPA, 2011d).

6.5.4 Conclusions Regarding Environmental Benefits

The environmental benefits of reducing BC are likely to be substantial, both in terms of the range of impacts avoided and the value to society, although it is difficult to quantify these impacts currently. Due to the difficulties involved in quantifying and valuing environmental benefits, EPA often addresses these benefits qualitatively with the exception of visibility benefits as previously discussed.

6.6 Conclusions

All control measures that reduce $PM_{2.5}$ pollution are virtually certain to achieve health benefits, and several studies examining costs and benefits of BC mitigation suggest that the health benefits alone may justify mitigation. Programs to reduce fine particles in the United States and in other developed countries have greatly reduced the negative health impacts of $PM_{2.5}$, including BC. EPA has determined that there is insufficient information at present to differentiate the health effects of the various constituents of $PM_{2.5}$; thus, EPA assumes that many constituents are associated with adverse health impacts. New programs introduced by EPA for mobile and stationary sources will continue to reduce $PM_{2.5}$-related health impacts in the United States over the next several decades. The largest potential benefits of BC mitigation measures are achievable internationally, due to high emissions co-located with large populations, particularly in South and East Asia. More information on the benefits and costs of individual measure in each country is needed to support policy decisions made at the national level.

Estimating the climate benefits of BC mitigation is less well understood and less certain compared with estimating health benefits. However, several conclusions can be drawn from the literature examining the climate impacts of BC reductions. Current studies indicate that BC reductions can reduce the rate of climate change in the near-term. Controlling emissions from motor vehicles and residential burning of solid fuels is likely to benefit climate, though residential emissions are particularly difficult to estimate and errors in current understanding of the composition of emissions may affect this conclusion. Major industrial sources of BC, such as brick kilns and coke ovens, will likely also lead to climate benefits. There are several key uncertainties which further research is needed to address, including the extent to which different emissions mixtures result in equivalent climate effects, how the indirect effects of those mixtures influence the climate outcomes, and the potential benefit of various mitigation strategies for precipitation and meteorology. Additional work is needed to design approaches to valuing climate impacts of BC directly, and to incorporate those approaches into useful metrics for evaluating policy decisions, similar to the social cost of carbon (SCC). It is also important to note that BC mitigation cannot substitute for CO_2 reductions for the purposes of alleviating long-term warming. The literature suggests that mitigating both short-lived climate forcers and long-lived greenhouse gases is necessary to achieve internationally agreed upon goals of temperature rise.

Overall, the literature points to substantial health and climate benefits of BC mitigation from some sources, particularly for control measures targeting emissions from motor vehicles, residential combustion of solid fuels, and some high BC-emitting industrial sources such as brick kilns and coke ovens. Mitigation measures for each of these sectors exist and have been proven to be effective in different parts of the world, including in the United States, as detailed in Chapters 8-11. Chapter 7 describes how the information presented in this chapter can be used to evaluate policy options.