Chapter 12

Key Black Carbon Mitigation Opportunities and Areas for Further Research

12.1 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.

- Effective control technologies and approaches are available to reduce BC emissions from a number of key source categories.

  - BC emissions reductions are generally achieved by applying technologies and strategies to improve combustion and/or control direct $PM_{2.5}$ emissions from sources. These and other mitigation approaches could be utilized to achieve further BC reductions, both in the United States and globally.

  - BC mitigation solutions vary significantly by region, and must be adapted based on the specific needs and implementation challenges faced by individual countries. Some source categories, such as mobile diesel engines, can be controlled with similar strategies around the world. Other source categories, such as improved stoves for residential heating and cooking, will require tailored solutions designed to address local needs and challenges. Further work is needed to refine these options to identify which might be best-suited to particular locations or situations.

- Achieving further BC reductions, both domestically and globally, will require adding a specific focus on reducing *direct* $PM_{2.5}$ emissions to overarching fine particle control programs.

  - BC reductions that have occurred to date (largely in developed countries) are mainly due to control programs aimed at $PM_{2.5}$, not targeted efforts to reduce BC per se. Greater attention to BC-focused strategies has the potential to help protect the climate (via the BC reductions achieved through direct $PM_{2.5}$ controls) while ensuring continued improvements in public health (via control of direct $PM_{2.5}$ in highly populated areas). Even if such controls are more costly than controls on secondary PM precursors, the combined public health and climate benefits may justify the expense.

- The options identified in this report for reducing BC emissions are consistent with control opportunities emphasized in other recent assessments. These represent important mitigation opportunities for key world regions, including the United States.

  - **United States:** Based on current inventories and control technologies, mobile diesel engines (on-road and nonroad, commercial marine, locomotives) represent the largest potential area of BC mitigation in the United States. Forthcoming controls on new mobile diesel engines are expected to reduce these emissions by 86% by 2030. Diesel retrofit programs for in-use mobile sources are a valuable complement to new engine standards for reducing emissions. Other source categories, including emissions from stationary sources (ICI boilers, stationary diesel engines, uncontrolled coal-fired EGUs) and residential wood combustion (hydronic heaters and woodstoves), also offer potential opportunities, but on a smaller scale due to fewer remaining emissions in these categories, or limits on control strategies that are cost-effective or easy to implement.

  - **Globally:** The suite of options for reducing BC emissions globally is broader than those used in the United States, and will vary by region. Key BC emissions reduction opportunities globally include residential cookstoves in all regions; brick kilns and coke ovens in Asia; and mobile diesels in all regions. While a variety of other opportunities may exist in individual countries or regions, these sectors account for a large portion of BC emissions, and studies have clearly indicated the benefits of mitigating these sources.

- **Sensitive Regions:** To address impacts in the Arctic, other assessments have identified the transportation sector (land-based diesel engines and Arctic shipping); residential heating (wood-fired stoves and boilers); and forest, grassland and agricultural burning as primary mitigation opportunities. In the Himalayas, studies have focused on residential cooking; industrial sources (especially coal-fired brick kilns); and transportation, primarily on-road and off-road diesel engines.

- A variety of other options may also be suitable and cost-effective for reducing BC emissions, but these can only be identified with a tailored assessment that accounts for individual countries' resources and needs.
  - Some potential sectors of interest include agricultural burning, oil and gas flaring, and stationary diesel engines in the Arctic far north.

- Key remaining uncertainties include:
  - Atmospheric processes affecting BC concentrations (e.g., transport and deposition)
  - Aerosol-cloud interactions (e.g., radiative and precipitation effects)
  - Climate effects of aerosol mixing state
  - Emissions of BC and co-emitted pollutants from specific regions, sources
  - Warming effect of non-BC aerosols in Arctic
  - Impacts of BC on snow and ice albedo
  - BrC climate impacts
  - Shape and magnitude of PM health impact function
  - Differential toxicity of PM components and mixtures
  - Impacts of BC on ecosystems and crops (dimming)

- Important policy-relevant research needs include:
  - Continued investigation of basic microphysical and atmospheric processes affecting BC and other aerosol species to support the development of improved estimates of radiative impacts, particularly indirect effects.
  - Improving global, regional, and domestic BC emissions inventories with more laboratory and field data on activity levels, operating conditions, and technological configurations, coupled with better estimation techniques for current and future emissions.
  - Focused investigations of the climate impacts of brown carbon (BrC).
  - Research on the impact of aerosols in snow- and ice-covered regions such as the Arctic.
  - Standardized definitions and improved instrumentation and measurement techniques for light-absorbing PM, coupled with expanded observations.
  - Continued investigation of the differential toxicity of PM components and mixtures and the shape and magnitude of the PM health impact function.
  - More detailed analysis and comparison of the costs and benefits of mitigating BC from specific types of sources in specific locations.
  - Refinement of policy-driven metrics relevant for BC and other short-lived climate forcers.
  - Analysis of key uncertainties.

12.2 Introduction

Based on currently available evidence, 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. The existing literature indicates that carefully designed programs that consider the full air pollution mixture (including BC, OC, and other co-pollutants) can slow near-term climate change while simultaneously achieving lasting public health and environmental benefits. Furthermore, currently available control technologies and mitigation approaches have already been shown to be effective in reducing BC emissions, often at quite reasonable costs. These and other mitigation approaches could be utilized to achieve further BC reductions. In the United States and Europe, significant reductions in BC emissions are already expected to occur over the coming decades as existing regulations such as those on diesel emissions are implemented. Some of these same approaches could help reduce emissions in developing countries, although the source mix is significantly different and additional approaches are needed to address developing countries' needs.

As discussed in Chapter 6, studies looking at global or regional BC emissions reduction scenarios have clearly demonstrated large potential climate and health benefits. The framework discussed in Chapter 7 suggests that policymakers have to consider a number of factors in designing control programs to achieve those benefits. There is no one-size-fits-all mitigation prescription; rather, there is a portfolio of mitigation opportunities, all of which have the potential to provide climate, health and environmental benefits if applied in appropriate locations. Chapters 8-11 illustrate the range of sources, technologies, and control options that policymakers can consider for purposes of BC mitigation.

This chapter brings all of this information together to identify paths forward on BC, based on the best available information about remaining emissions and cost-effective mitigation opportunities. The options identified in this report for reducing BC emissions are consistent with control opportunities emphasized in other assessments, including UNEP/WMO (2011a), LRTAP (2010), USAID (2010a), the Arctic Council (2011), Quinn et al. (2011), and U.S. EPA (2011b). BC mitigation solutions vary significantly by region, and must be adapted based on the specific needs and implementation challenges faced by individual countries. Some source categories, such as improved stoves for residential heating and cooking, will require tailored solutions designed to address local needs and challenges. Further work is needed to refine these options to identify which might be best-suited to particular locations or situations. The recently completed UNEP synthesis report, *Actions for Controlling Short-Lived Climate Forcers*, that identifies regionally appropriate mitigation options for BC can provide important information toward this goal (see UNEP, 2011).

12.3 Controlling Black Carbon as Part of Broader $PM_{2.5}$ Mitigation Program

As discussed in Chapter 7, policymakers designing BC mitigation strategies have a number of separate goals (health, climate, environment) and a variety of alternative approaches to consider. Many of the BC emissions reductions currently being achieved are the result of broader programs or strategies aimed at reducing overall $PM_{2.5}$, primarily for purposes of protecting public health. This raises a very important question, namely: are existing $PM_{2.5}$ control programs and strategies (widely implemented) sufficient to control BC to protect climate, or are alternative strategies and approaches needed to guarantee BC reductions? Asked another way: what might policymakers do differently with regard to BC controls in order to jointly maximize climate and public health benefits? The degree of overlap between programs and measures driven by public health protection vs. climate goals is of critical importance.

In the United States and other developed countries, $PM_{2.5}$ control programs have focused very heavily on reductions in emissions of NO_x and SO_x, which contribute to secondary $PM_{2.5}$ formation. There are several reasons for this: first, NO_x and SO_x emissions from utilities and other major industrial sources contribute the bulk of $PM_{2.5}$ mass in most areas; second, they are the pollutants principally responsible for regional transport of $PM_{2.5}$, and therefore have been the focus of national rules; third, reductions in NO_x and SO_x are highly cost-effective. Widespread reductions in NO_x and SO_x emissions have been credited with substantial decreases in ambient $PM_{2.5}$ concentrations, reductions in acid deposition, and dramatic improvements in public health and the environment (U.S. EPA, 2011c, e). In both the United States and Europe, programs to reduce emissions of NO_x and SO_x continue to serve as cornerstones of $PM_{2.5}$ air quality improvement programs. However, these programs have relatively little impact on BC emissions. This is due to a difference in major emitting sources, and also the types of controls applied, which may not be highly effective in reducing direct particle emissions (including BC and OC).

The other major component of existing $PM_{2.5}$ control programs is the effort to reduce emissions from mobile sources, including diesel vehicles (on-road diesels, nonroad diesels, commercial marine, and locomotives) but also gasoline vehicles. These programs, which have been adopted in both the United States and Europe, have led to stringent controls on NO_x emissions, contributing to the overall decline in NO_x and SO_x emissions discussed above. In addition, controls on mobile sources (particularly diesels) have been highly effective in controlling BC emissions. Mobile source control programs are principally responsible for the dramatic reductions in BC emissions projected to occur in the United States and Europe by 2030. These reductions have been tied to substantial public health benefits (U.S. EPA, 2007). In addition, controls on certain industrial processes have contributed substantially to reductions in direct $PM_{2.5}$ emissions (U.S. EPA, 2004b).

As $PM_{2.5}$ control programs in developed countries have matured, the mix of sources controlled has gradually changed, and can be expected to change further in coming decades. In the United States, state and local areas have already been turning to controls on direct $PM_{2.5}$ emissions as a means of dealing with persistent nonattainment problems. Areas such as Detroit, Michigan; St. Louis, Illinois; Pittsburgh, Pennsylvania (Liberty-Clairton); and Birmingham, Alabama have either included or have been planning to include emissions controls of direct $PM_{2.5}$ in their State Implementation Plans (SIPs) to demonstrate future compliance of the PM NAAQS.[1,2,3,4] These control strategies include emissions controls on industrial sources such as steel mills, coke oven batteries, and foundries, and will reduce BC, OC and toxic metals. Because many of these sources are also located in urban areas where significant numbers of people reside, substantial public health benefits are also expected from these emissions controls (Fann et al., 2011). As discussed in Chapter 6, EPA's health-based $ per ton benefits estimates indicate that these reductions typically can provide higher levels of health benefits per ton of emissions reduction as compared to reductions from other sources.

For developed countries, then, it appears that control programs are gradually evolving in a direction toward controls that achieve large BC reductions, and that these countries are on track to have very stringent controls on, and significant reductions from, many source categories. Some of these reductions will not be fully in place for several decades, which creates opportunities for incentive programs to accelerate the reductions. Thus, there may be hybrid strategies the United States and other countries can adopt that will both increase public health benefits (via control of direct $PM_{2.5}$ in highly populated areas) and protect the climate (via the BC reductions achieved through direct $PM_{2.5}$ controls). Even if such controls are more costly than controls on secondary PM precursors, the extra public health and climate benefits may justify the expense.

In developing countries, the $PM_{2.5}$ challenges are somewhat different. Overall ambient $PM_{2.5}$ and BC concentrations are generally higher than in developed countries, and $PM_{2.5}$ control programs are less advanced. For example, some megacities in Asia have annual average $PM_{2.5}$ concentrations above 100 $\mu g/m^3$, more than six times the air quality standard in the United States (ESMAP, 2004). Moreover, the mix of sources is quite different, requiring different mitigation strategies. For example, mobile sources often have relatively little emissions control currently. Furthermore, there are many more small BC sources like kilns and cookstoves that could be replaced entirely with more advanced technologies. Coal use is very high, and significant air quality improvements could be obtained through switching to cleaner fuels. These changes have already occurred in developed countries. In general, the public health opportunities of $PM_{2.5}$ reductions in developing countries are large, and controls on BC and other directly emitted $PM_{2.5}$ could provide significant public health improvements. This presents a real win-win opportunity, since BC reductions will provide benefits to climate as well as to public health.

It is clear, therefore, that emphasizing BC reductions within broader $PM_{2.5}$ control programs might be a beneficial strategy for health and climate in both developed and developing countries. However, because of the significant differences in the sources, emissions, technologies, costs, and implementation challenges for BC reductions in different countries and regions, the top-tier mitigation options—those that can reliably achieve the largest climate, health and environmental benefits at low cost—will vary among regions. In some cases, options can clearly be discounted in some regions due to low effectiveness or high costs. In other cases, barriers to implementation or simply insufficient information about potential effectiveness can render certain choices less attractive. When all these factors are considered, the number of clearly beneficial mitigation options can be narrowed down significantly. The remaining mitigation options present the clearest near-term opportunities to achieve benefits for climate and public health in specific regions.

12.4 Key Black Carbon Mitigation Opportunities

The control strategies described in detail in Chapters 8-11 reflect the range of existing mitigation options for BC emissions. Based on the BC emissions profile of key world regions, the technologies available (including their cost and demonstrated effectiveness), and the implementation challenges discussed in these earlier chapters, a wide variety of $PM_{2.5}$ mitigation measures appear likely to provide substantial benefits to human health and

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[1] Michigan Department of Environmental Quality Air Quality Division Draft State Implementation Plan Submittal for Fine Particulate Matter. Available online at: *http://michigan.gov/documents/deq/deq-aqd-air-aqe-sip-pm25-1-14-08_223446_7.pdf.*

[2] United States Steel Corporation Granite City Works and Illinois EPA Memorandum of Understanding.

[3] Revision to the Allegheny County Portion of the Pennsylvania State Implementation Plan; Attainment Demonstration for the Liberty-Clariton $PM_{2.5}$ Nonattainment Area. Available online at: *http://www.achd.net/airqual/Liberty-Clairton_PM2.5_SIP-Apr2011.pdf.*

[4] Alabama State Implementation Plan for $PM_{2.5}$ for Birmingham, Alabama.

the environment. A smaller subset of measures—those that affect BC-rich sources and/or emissions in sensitive regions—are the most likely to simultaneously provide climate benefits. Measures that promise both climate and health benefits can be considered "win-win" opportunities, and the lower the uncertainty around those measures (with regard to effectiveness, cost, etc.), the greater the confidence with which policymakers can move forward. Low-cost measures for which there is relatively high certainty of climate as well as health and environmental benefits can be considered "top tier" opportunities. This section discusses potential top-tier mitigation options for key world regions, including the United States. A variety of other options may also be suitable and cost-effective for reducing BC emissions, so this discussion should not be seen as limiting or discouraging further exploration or adoption of other measures. Rather, it is intended to help clarify the "low-hanging fruit" of BC mitigation opportunities. Importantly, these opportunities are described in general terms, aimed at highlighting sectors and regions where mitigation holds particular promise. Individual countries' strategies are likely to look different based on their application of the factors outlined in the mitigation framework in Chapter 7. Each country will have a variety of sector- and technology-specific opportunities that can only be identified with a tailored assessment.

12.4.1 U.S. Black Carbon Mitigation Opportunities

Based on current inventories and control technologies, mobile diesel engines represent the largest potential area of BC mitigation in the United States. Other source categories, stationary sources and residential wood combustion, also offer potential emissions reduction opportunities, but on a smaller scale due to smaller remaining emissions in these categories, or limits on control strategies that are cost effective or easy to implement. Due to U.S. air quality regulations, a number of controls on all of these source categories are already planned over the next decade or two. However, further reductions may be possible, for example with more dedicated funding for diesel retrofits on existing engines. Chapter 6 indicated that BC reductions in the U.S. have the potential to provide large public health benefits domestically, and climate benefits in terms of global average radiative forcing and impacts in the Arctic.

- **Mobile engines: On-road and Nonroad, Commercial Marine, Locomotives:** The United States has already enacted stringent standards for *new mobile source diesel engines* that are projected to reduce BC emissions by 86% between 2005 and 2030 as the existing diesel fleet is replaced by these new engines. Though the standards do not dictate the use of a specific technology, the mobile source reductions will be achieved mostly from DPFs on new diesel engines, in conjunction with ultra low sulfur diesel fuel. EPA has estimated the cost of controlling $PM_{2.5}$ from diesel engines via new engine requirements at about $14,000/ton (2010$) (including the cost of ULSD fuel). The public health benefits of these reductions have been estimated at $290 billion annually in 2030(2010$).

  For the existing legacy *in-use mobile diesel fleet* in the United States, programs such as EPA's National Clean Diesel Campaign and the SmartWay Transport Partnership Program can help achieve additional emissions reductions through retrofits on an estimated 11 million engines. DPFs can reduce $PM_{2.5}$ emissions by up to 99%, at a cost of $8,000 to $15,000 for passive DPFs, and $20,000 to $50,000 for active DPF systems (2010$). However, not all engines are good candidates for DPFs because of old age or poor maintenance.

- **Stationary sources: ICI Boilers, Stationary Diesel Engines, Uncontrolled Coal-Fired EGUs:** Stationary source BC emissions in the United States have declined dramatically in the last century. Remaining emissions constitute 8% of the inventory and come primarily from coal combustion (utilities, industrial/commercial boilers, other industrial processes) and stationary diesel engines. Available control technologies and strategies include direct $PM_{2.5}$ reduction technologies such as fabric filters (also known as baghouses), electrostatic precipitators, and DPFs. These strategies range in cost from as little as $48 per ton $PM_{2.5}$ to over $24,000 per ton $PM_{2.5}$ (2010$), depending on the source category. They may also involve millions of dollars in initial capital costs. As mentioned above, controls on direct $PM_{2.5}$ from industrial sources are being considered by a number of states as a strategy for addressing persistent nonattainment problems in key areas.

- **Residential Wood Combustion: Hydronic Heaters and Wood Stoves:** *Residential wood combustion* (RWC) represents a small portion (3%) of the U.S. BC inventory, but mitigation opportunities are available. In part because seasonal use of these sources is concentrated in northern areas, reducing emissions may reduce deposition on snow and ice. EPA has already established emissions standards for new residential wood stoves and is working to revise and expand these standards to include all residential wood heaters, including hydronic heaters and furnaces, as well as stoves. Mitigation strategies for RWC sources include providing alternatives to wood, replacing inefficient units (wood stoves, hydronic heaters) with newer, cleaner units through voluntary or subsidized change-out programs, or retrofitting existing units to enable use of alternative fuels such as natural gas (fireplaces). New EPA-certified wood stoves have a cost of about $3,600 per ton $PM_{2.5}$, while gas fireplace inserts average $1,800 per ton $PM_{2.5}$ (2010$).

12.4.2 Global Black Carbon Mitigation Opportunities

Outside of the United States, BC emissions are increasing in some locations as a result of rapid economic development coupled with the lack of serious $PM_{2.5}$ mitigation measures. The magnitude of these emissions translates into very substantial impacts to climate, public health, and the environment, particularly in Asia. Global BC mitigation opportunities can be evaluated in two ways: first, in terms of major source types within key emitting regions (i.e., the largest reduction opportunities on a total emissions basis), and second, by focusing on emissions affecting sensitive regions (i.e., the best targeted opportunities in terms of avoiding critical impacts). It is important to note that effective BC mitigation at the global scale will depend on application of *a variety of strategies* rather than widespread adoption of a single strategy.

In terms of major emitting sectors/regions, there are significant differences in emissions and mitigation potential based on the level of development of the emitting country(s). Opportunities in developed regions such as Europe and Russia are in many ways similar to those in the United States: mobile diesel engines are very important, as are emissions from boilers, stationary diesel engines, and residential wood combustion (though the order of importance varies by country). In general, European countries have emissions patterns and control programs that are similar to the United States, though the timing of planned emissions reductions may vary. Russia is distinctive in that it may also have significant mitigation potential in the area of agricultural burning: emissions from this source category in Russia are thought to be large and potentially very significant for the Arctic (CATF, 2009a). However, significant uncertainties hinder mitigation actions in this area at present.

In the developing world, the main BC-emitting sectors internationally are residential solid fuel combustion (cookstoves), industry, and transportation. Mitigation measures to reduce emissions from each of these sectors are presently available and feasible on wide scales. Opportunities in Asia range from mobile diesel engines to industrial sources (especially brick kilns) to residential cooking on traditional stoves. This region is of particular importance for BC mitigation, both because it accounts for approximately 40% of global BC emissions and because of the effect of these on the Himalayas and the Arctic. In Africa and Latin America, emissions come largely from open biomass burning and residential cookstoves. While large, these emissions may be challenging to mitigate, particularly those from open biomass burning (see Chapter 11).

In considering which source categories and locations offer the largest opportunities, it is important to remember that there are significant differences in control opportunities between developed and developing countries. Options that are feasible in the United States and Europe may not be appropriate for application in developing countries due to cost constraints or other barriers. For example, advanced industrial emissions control systems may not be applicable to source types in developing countries, or the costs of installing such systems may be prohibitive. It is also important to note that the opportunities for BC reductions may change as countries develop. For example, currently developing countries have a higher concentration of emissions in the residential and industrial sectors, but the growth of the mobile source sector in these countries may lead to an increase in their overall BC emissions and a shift in the relative importance of specific BC-emitting sources over the next several decades. Finally, it is important to remember that cost, emissions and other relevant data are not as widely available internationally, which makes assessment of top-tier mitigation options outside the United States and Europe more difficult.

Several groups have developed preliminary analyses of global strategies to reduce BC emissions (Rypdal et al., 2005; Kandlikar et al., 2009; Cofala et al., 2007; Baron et al., 2009; UNEP/WMO, 2011; Shindell, 2012). These assessments have generally found the largest BC reductions at lower costs in Asia, which has high emissions from residential cooking and heating as well as poorly controlled transportation and small industrial sources. Some of these assessments also included measures to reduce biomass burning in Africa and South America. BC strategies ranged from improved combustion to add-on particle controls. The actual benefits to global or regional climate resulting from such strategies can, however, vary significantly with the nature of the co-pollutants emitted from different sources, their location, and the nature of the controls.

Based on currently available information, key emissions reduction opportunities internationally may include:

- **Residential Cookstoves in All Regions:** Replacing traditional cookstoves, which account for 25% of total global BC emissions, with more advanced technologies is one of the most promising opportunities internationally, in large part because of the enormous public health benefits that could result from cooking with cleaner fuels and stoves. This strategy may provide particularly large benefits in Asia (including China and India), given the proximity of these sources to both large populations and climate-sensitive regions (the Himalayas). Exposures to cookstove emissions currently lead to an estimated 2 million deaths each year. In Asia, these emissions are also linked to the devastating impacts of ABCs, including the disruption of the Indian monsoon. While there is still uncertainty about BC emissions emanating from different stove and fuel types, cookstoves also emit CO_2 and CH_4, contributing to climate effects, and a variety of aerosols and gases (SO_2, NO_x, CO, OC) which contribute to adverse health and environmental effects. Reducing cookstove emissions helps to alleviate all of these impacts. The magnitude of the health benefits alone justifies the cost of cookstove replacement on large scales.

  While the world-wide stove market is approximately 500-800 million households, current programs likely replace only approximately 5-10 million improved stoves per year. Significant expansion of such programs utilizing locally appropriate advanced stove technologies and fuels could achieve large-scale climate, health and environmental benefits. The costs range from $8-$100+ per stove. Improved cookstove technologies all face important supply, cost, performance, usability, marketability and other barriers that have impeded progress in the past. However, a number of factors point to much greater potential to achieve large-scale success in this sector today. Along with many corporations and world governments, the U.S. government has made a substantial diplomatic, research, and financing commitment to the Global Alliance for Clean Cookstoves, which has an interim goal of having 100 million homes adopt clean and efficient cooking solutions by 2020.[5] Continued investment in the Alliance will help achieve this goal with great public health benefits.

- **Brick Kilns and Coke Ovens in Asia:** Emissions from stationary sources represent 20% of the global inventory, and several recent studies have identified brick kilns and coke ovens as two large contributing source categories for which new, clean technologies are available to reduce BC emissions at reasonable cost. Brick kilns can be replaced by cleaner vertical shaft kilns or Hoffman kilns. Coke ovens can be designed with modern recovery ovens or the use of end-of-pipe control technologies. Since the ratio of BC to other PM constituents co-emitted by these sources (such as OC, SO_2 and NO_x) is high, mitigation measures for brick kilns and coke ovens are likely to result in both climate and health benefits. Furthermore, the health benefits of emissions reductions in these sectors—both for workers and for exposed local populations—may offset mitigation costs.

- **Mobile Diesel Engines in All Regions:** Mobile sources account for approximately 18% of the global BC inventory, and both new engine standards and retrofits of existing engines/vehicles could help reduce these emissions. In the United States and Europe, mitigation programs are already underway. Many other countries have begun the phase-in of emissions standards and ULSD fuel, which is a prerequisite for the proper functioning of DPFs. However, these requirements lag behind in some regions, as do on-the-ground deployment of DPFs and ULSD. As a result, there remains significant opportunity internationally to accelerate the deployment of clean engines and fuels. Similar to stationary sources, these emissions are often co-located with large populations, making them a prime target for mitigation programs motivated by both climate and public health concerns. Mobile source mitigation opportunities are likely to vary among countries. In some regions, on-road sources such as diesel trucks may be the dominant mobile BC emissions source, while in other regions, non-road sources such as locomotives may be particularly important. In general, other countries could achieve further BC reductions by implementing standards for nonroad diesels, locomotive, and commercial marine vessels (categories 1 and 2).

In terms of mitigation measures aimed at protecting particularly sensitive regions, most of the attention

[5] See *http://cleancookstoves.org*.

to date has been directed at two main world regions: the Arctic and the Himalayas. Available studies suggest that there are considerable differences between the prime mitigation opportunities for these two regions.

In the **Arctic**, recent work by the Arctic Monitoring and Assessment Program (AMAP) has indicated that mitigation measures *near or within* the Arctic will provide the largest benefits for the region. This is because 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 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). Importantly, studies have also found 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. Similarly, sulfate aerosol, which normally exerts a cooling influence, appears to have a much weaker effect over snow and ice (Quinn et al., 2011, p. 101-2). This means that a wide array of measures aimed at reducing PM in or near the Arctic will provide benefits to the Arctic region. In accord with the modeling results from AMAP (Quinn et al., 2011), the Arctic Council Task Force on SLCF has specifically recommended that Arctic Council countries—including the United States, Canada, Russia, Sweden, Norway, Denmark, and Iceland—pursue additional emissions reductions from the following sources (Arctic Council, 2011):

- **Transportation, including land-based diesel engines and Arctic shipping:** While noting that most Arctic nations have already adopted and begun implementing regulations for new diesel engines, the Task Force stressed the benefits of retrofitting or retiring older vehicles and equipment, accelerating the phase-in of ultra low sulfur diesel fuels, and expanding control requirements to additional source categories, such as marine vessels and locomotives, as appropriate. The Task Force noted that although BC emissions from marine shipping are currently small, they occur in direct proximity to snow and ice and are expected to increase in future due to declining summer sea ice in the Arctic. As a result, the Task Force recommended a number of measures aimed specifically at limiting BC emissions from Arctic shipping.

- **Residential heating:** Emissions inventories for Arctic countries indicate that wood-fired stoves and boilers are a major source of BC in the Arctic. The Task Force recommended Arctic countries consider implementing stringent BC emissions standards for stoves and boilers, adopt point-of-manufacture performance standards, and work to develop new technologies and incentive programs to replace old stoves and boilers.

- **Forest, grassland and agricultural burning:** The Task Force identified a variety of techniques that could be utilized to reduce emissions from open biomass burning, a leading source of BC in the Arctic. Available measures include technical assistance, demonstration projects, and financing to encourage no-burn methods, such as conservation tillage or soil incorporation; information campaigns to prevent accidental wildfires and unnecessary use of fire as a land management technique; and expansion of resources for fire monitoring, fire management, and fire response.

Reductions outside of the Arctic will also provide benefits to the Arctic region. The AMAP (Quinn et al., 2011) modeling indicates that BC emissions from outside the Arctic Council nations are contributing (in aggregate) the most to total radiative forcing (warming) in the region (see Chapter 2). This suggests that reductions in BC emissions from regions other than the Arctic itself (60°-90°N) will be effective in reducing Arctic warming; thus, BC reductions anywhere—including the measures listed earlier in this chapter—can be expected to provide benefits specifically to the Arctic region.

For the **Himalayas**, most of the attention has focused on the three source categories mentioned above as important for mitigation globally: residential cookstoves, brick kilns, and mobile diesel engines. USAID (2010a) and U.S. EPA (201b) have both identified a number of measures that could provide substantial climate, health and environmental benefits in this region. Specifically, these opportunities include:

- **Residential cooking:** Cookstoves are the largest source of BC emissions in Asia, and therefore offer the largest overall emissions reduction opportunity in the region. Furthermore, according to USAID, "household fuel and stove interventions … appear to consistently achieve the highest reduction in black carbon emissions per unit cost. This finding holds true for all stove and fuel interventions examined" (USAID, 2010a, p. 3). The study found that these interventions "yield the highest net benefits per unit intervention cost if health benefits are included" (p. 4) and that the GHG co-benefits are also large. All of these factors indicate that the residential sector is a prime opportunity for BC mitigation.

- **Industrial sources, particularly coal-fired brick kilns:** Small-scale industrial sources have been identified as major emitters of BC, with particular attention given to mitigation potential from traditional brick kilns. Adopting more efficient technologies, using cleaner fuels, and improving operating practices may help to reduce BC emissions from this sector. In addition, product substitution may allow for greater efficiency and cleaner production (Heierli and Maithel, 2008). The largest BC emissions reductions can be achieved through substitution of Vertical Shaft Brick Kilns (VSBKs), Hoffmann kilns, or tunnel kilns for traditional Bull's Trench Kilns (BTKs) (U.S. EPA, 2011b). However, even traditional kilns can produce lower emissions with proper fuels and operating procedures.

- **Transportation, primarily on-road and off-road diesel engines:** In Asia, the main focus in the mobile sector is land-based vehicles, especially long-haul trucks and buses (U.S. EPA, 2011b). USAID (2010a) identified a number of measures aimed at mobile sources as falling in the "next tier" of BC abatement measures after residential cookstove interventions. Specifically, the study pointed to the need for more stringent emissions standards, greater use of DPFs for new and existing (retrofitted) diesel vehicles, and a shift toward cleaner fuels such as compressed natural gas (CNG) or liquefied petroleum gas (LPG). However, the study also noted that ULSD fuel is not available in Asia except in a few major metropolitan areas and called for efforts to promote desulfurization in the region (USAID, 2010a). U.S. EPA (2011b) noted that substantial efficiency improvements and reductions in BC emissions could be achieved through improvements in fleet logistics, such as eliminating "deadheading" (i.e. trips with no load).

12.4.3 Other Mitigation Options

The source categories listed above for the United States and other world regions offer the greatest certainty of BC reductions that are likely to be beneficial for climate. Mitigation measures aimed at reducing BC emissions in sectors beyond those listed above require further investigation. The effectiveness of controls in other BC emissions source categories is far less certain, and the costs and implementation barriers potentially higher. Some may be highly effective if designed and implemented correctly.

Several studies have suggested that controlling **agricultural burning** could provide important climate benefits (Warneke et al., 2010; CATF, 2009a). Since open biomass burning is the largest source of BC emissions globally, accounting for over 35% of the inventory, actions to reduce emissions from this sector have the potential to make a significant difference. However, it is also important to recognize that emissions of OC are seven times higher than BC emissions from this sector, and that a large portion of emissions come from wildfires. In the United States, for example, wildfires contribute about 68% of total BC emissions from open biomass burning. Presently, data on the percent of land area affected by different types of burning are very limited, and little is known about how specific measures would impact climate, both globally and regionally. Appropriate mitigation measures are highly dependent on a number of variables, including timing and location of burning, resource management objectives, vegetation type, and available resources. The costs of mitigation measures are uncertain and potentially high, as they depend on various site-specific factors. Thus, despite the significant contribution of open biomass burning to BC emissions worldwide, further investigation into specific options is needed to identify feasible mitigation opportunities in appropriate locations. Successful implementation of mitigation approaches in world regions where biomass burning is widespread will require training in proper burning techniques and tools to ensure effective and appropriate use of prescribed fire.

Another sector that has drawn attention, especially with regard to potential impacts in the Arctic, is **oil and gas flaring**. Despite higher uncertainty about the magnitude and impact of BC emissions from flaring, the Arctic Council Task Force on SLCF recommended that this source be evaluated carefully due to the expansion of oil and gas extraction activities in the Arctic region (Arctic Council, 2011).

Other categories of interest include **stationary diesel engines** in the Arctic far North. These sources are located in proximity to snow and ice, are often very expensive to operate due to fuel transport requirements, and may adversely impact the health of indigenous communities.

12.5 Key Policy-Relevant Scientific Uncertainties

Many uncertainties are associated with understanding the effects of BC emissions on air quality, climate, health, and the environment. Some of these may be important and large enough to influence BC mitigation decisions – including the decision about whether to invest in BC mitigation at all as well as the selection of specific mitigation

	Less certain	More certain
More likely to be important for BC mitigation decisions	• Emissions of BC and co-emitted pollutants from specific regions, sources • Aerosol-cloud interactions (e.g., radiative and precipitation effects) • Climate effects of aerosol mixing state	• Impacts of BC on snow and ice albedo • Shape and magnitude of PM health impact function
Less likely to be important for BC mitigation decisions	• Warming effect of non-BC aerosols in Arctic • BrC climate impacts • Differential toxicity of PM components and mixtures • Impacts of BC on ecosystems and crops (dimming)	• Atmospheric processes affecting BC concentrations (e.g., transport and deposition)

Key
- Uncertainties related to Emissions and Concentrations
- Uncertainties related to Climate Effects
- Uncertainties related to Health and Environmental Effects

Figure 12-1. Key Policy-Relevant Scientific Uncertainties Related to BC. (Source: U.S. EPA)

strategies. Other uncertainties may be important scientific questions, but would be unlikely to influence BC mitigation decisions.

Figure 12-1 roughly groups key uncertainties identified in this report by level of uncertainty and likelihood to affect BC mitigation decisions. Each of these uncertainties pertains to an important aspect of BC – emissions and concentrations, climate effects, or health and environmental effects. Uncertainties categorized as "less certain" and "more likely to be important for BC mitigation decisions" are those for which new information can change our understanding of the direction and effectiveness of BC mitigation in terms of climate, health, and environmental benefits. These are the uncertainties that are the highest priorities for future research. For example, understanding the magnitude of BC emissions from specific regions and sectors, along with co-emitted pollutants (e.g. OC and BrC), is critical to estimating the net warming or cooling effect of that source. New information showing a larger fraction of warming agents among the emitted mixture from a particular source may make mitigation more attractive from a climate perspective; similarly, a smaller relative contribution of warming agents from a source could make it a less attractive target for mitigation. Impacts of BC and other aerosols on clouds, both in terms of radiative forcing and impacts on precipitation, as well as the climate effects of different aerosol mixing states (e.g., possible enhanced absorption by BC when coated by sulfate), are also highly uncertain. Additional research in these areas has the potential to shift the current assessment of the climate benefits of BC mitigation in important ways.

Uncertainties categorized as "less certain" and "less likely to be important for BC mitigation decisions" are those that are not well-understood but for which new information is unlikely to fundamentally change our understanding of BC mitigation impacts. In some cases, the outcome of new information may be to change our understanding of the magnitude of BC mitigation impacts of climate, health, and the environment, but not the direction of these benefits. For example, new information may improve understanding of the effects of non-BC aerosols (e.g., OC, BrC, sulfate) in the Arctic, both in terms of impacts on snow and ice albedo, as well as the pace of melting. Since all particles are generally darker than snow and ice, additional information could change the magnitude of estimated BC mitigation benefits in the Arctic. Similarly, if a broader range of aerosols are confirmed to contribute to warming in the Arctic, it would strengthen evidence that mitigating BC and related co-emitted pollutants could provide significant benefits to this region; however, such evidence would not necessarily change the highest priority mitigation measures aimed at BC-rich sources. Although differential toxicity of $PM_{2.5}$ components and mixtures is critical for understanding the magnitude of the health benefits achieved by controlling $PM_{2.5}$, the current literature points to health effects of BC that are similar to those of other $PM_{2.5}$ components. Since it is very likely that reductions in BC will be found to be health beneficial, new information on differential toxicity is less likely to affect BC mitigation decisions.

Uncertainties categorized as "more certain" are still significant, even if there is relatively more evidence on these topics as compared to those categorized as "less certain." For example, the impacts of BC on snow and ice are characterized by a small but generally consistent body of literature. There is a strong need for additional research in this area, even though currently available studies already suggest BC mitigation efforts will provide benefits in snow/ice covered areas. In addition, there remains some uncertainty regarding the full extent of $PM_{2.5}$ health effects, especially in the developing world. The health effects of $PM_{2.5}$ are generally well characterized as a result of numerous major long-term epidemiological studies conducted in developed countries and a number of short-term studies conducted in locations around the world. Thus the health effects of $PM_{2.5}$ are generally well-known and provide a strong basis for controlling emissions of PM precursors and components, including BC. However, the magnitude and shape of the concentration-response function in developing countries where exposure is significantly higher remains under investigation.

12.6 High Priority Research Needs for Black Carbon

There are a number of high priority research topics that could help advance efforts to control emissions from BC sources, clarify the impacts and benefits of BC mitigation, and reduce key remaining uncertainties, particularly those summarized in section 12.5 and in Figure 12-1. Some of these research topics pertain to key scientific aspects of BC, including composition, morphology, fate, and transport. Other important areas for further research relate directly to information and tools necessary for policymaking about BC. Research on these topics would allow for more informed policy decisions regarding mitigation of emissions of BC and related species. Based on the information reviewed for this report, EPA concludes that priority should be given to research in the following areas:

1. **Continued investigation of basic microphysical and atmospheric processes affecting BC and other aerosol species to support the development of improved estimates of radiative impacts, particularly indirect effects.**

Some of the basic microphysical and atmospheric processes that BC and other aerosol species undergo are not very well understood. This includes the mixing of BC with other aerosol species, the atmospheric aging of BC and how aging affects BC's climatic and health impacts, and interactions with cloud droplets and the hydrologic cycle in general. Incomplete understanding of the *climate effects of aerosol mixing state* and of *aerosol-cloud interactions* limits the scientific community's ability to model BC in the atmosphere and estimate its impacts. Few global models are now able to resolve the cloud microphysics which are of importance in determining climatic effects. Direct radiative forcing from BC is clearly positive and results in warming. However, early results indicate BC emissions lead to a net positive cloud absorption effect but both positive (warming) and negative (cooling) semi-direct and negative indirect effects. The net result may be negative enough to offset some of the warming due to the direct effects of BC. The net effect of BC on cloud absorption, semi-direct and indirect cloud feedbacks depends on many factors, among them aerosol hygroscopicity, absorptivity, and number concentration relative to background particles. Improvements in our understanding of these basic properties through controlled experiments and atmospheric observations could improve climate models, and could also inform ongoing efforts to investigate the health effects of PM constituents, including BC.

2. **Improving global, regional, and domestic BC emissions inventories with more laboratory and field data on activity levels, operating conditions, and technological configurations, coupled with better estimation techniques for current and future emissions.**

Given the diversity and ubiquity of sources of BC, accurately measuring and tracking *emissions of BC and its co-pollutants from specific source categories* is a very difficult undertaking. Emissions inventories in the United States and other developed countries account for most source categories, but considerable uncertainty remains. More information on both emission factors and usage would be helpful. In particular, emissions from key industrial sources, flaring, residential heating, and open biomass burning remain poorly characterized. In general, mobile source emissions are among the best characterized (especially in developed countries), but improved information is still needed for some sectors, such as nonroad mobile sources (aircraft, locomotives, ocean-going vessels); newer technology on-road diesel/gasoline vehicles; high-emitting vehicles; and vehicles operating at low temperatures.

Uncertainties are larger for BC inventories in developing countries and globally. For these inventories, priorities include better characterization of emissions from residential cookstoves, in-use mobile sources, small fires, smaller industrial sources such as brick kilns, and flaring emissions. For sources such as cookstoves, improved characterization depends critically on field-based measurements of emissions from in-use sources. In addition, usage patterns need to be reviewed to ensure that appropriate "activity" levels are applied to emission factors to arrive at final emissions estimates. Finally, fuller incorporation of regional inventories into global inventories could improve country- and region- specific emissions estimates.

Quantifying and reducing the uncertainties in global, regional, and domestic emissions inventories requires collecting source-specific emissions data from lab or field-based measurements and gathering information on activity levels, operating conditions, and technological configurations. For hard-to reach areas, improvements in estimation techniques could significantly improve global and regional inventories. Systematic collection and sharing of emissions data and meta-data is important for both scientific and policy purposes.

3. Focused investigations of the climate impacts of brown carbon (BrC).

The role of BrC is important for determining the potential climate benefit of mitigating sources with high OC emissions such as biomass burning. BrC may also play a stronger role in the Arctic and snow- and ice-covered regions, through deposition on ice and snow. Several aspects of the BrC issue warrant research in order to better characterize the *climate impacts of BrC*. First, multi-wavelength measurements are needed to separate and characterize BrC and BC. Reporting column data by wavelength may aid model-observation comparison, as BC and BrC differ in terms of peak absorption. Second, BrC should be incorporated into climate models, and the impact of BrC on net forcing estimated independently from the impact of BC. Atmospheric observations of BrC and experimental methodologies for determining BrC emissions are also needed, in conjunction with the improvements in BrC measurements and expanded observations, particularly in ice- and snow-covered regions (described further below).

4. Research on the impact of aerosols in snow- and ice-covered regions such as the Arctic.

Clarifying the role of BC, BrC, and other aerosols in sensitive regions such as the Arctic and the Himalayas is critically important for proper characterization of the role of different species in climate change in these regions. Additional work on BC impacts should be supplemented with expanded research on non-BC aerosols, including sulfate, nitrate, and OC (including BrC). An expanded observational record coupled with more thorough treatment of different aerosol species in climate models (both described elsewhere in this section) could help clarify the contribution of different species to net warming or cooling in the Arctic and could provide insight into effective mitigation measures. Key topics include the *impact of BC on snow and ice albedo* and the *warming impact of non-BC aerosols in the Arctic*.

5. Standardized definitions and improved instrumentation and measurement techniques for light-absorbing PM, coupled with expanded observations.

In order to accurately assess the impacts of BC (and co-pollutant) emissions, it is essential to have a clear understanding of the optical properties of atmospheric aerosols and be able to trace those to emissions from specific sources. Precise and consistent definitions and measurements of BC and other carbonaceous aerosols would ensure more accurate assessment of BC emissions, climate and public health impacts, and mitigation options. Additional research is needed to improve instrumentation and measurement techniques to quantify accurately the light-absorption properties of BC, BrC, and other aerosols; to harmonize measurement and reference methods to standardize definitions of BC, BrC and other compounds; and to refine measurement techniques to collect more data on light-absorption capacity of emissions from specific sources. Additional representative source measurements to better characterize BC emissions by source category, fuel type and combustion conditions can help improve emissions inventories and reduce modeling uncertainties.

It is equally important to expand the observational record for BC, including observations of atmospheric concentrations of BC and BC deposition. Existing measurements of BC are sparse in both spatial and temporal coverage, even in countries with more advanced monitoring programs such as the United States. An expanded observational record based on standardized measurement techniques and instruments could provide important information about BC transport, vertical distribution, atmospheric interactions, and deposition. Observations of BC and BrC deposition are important for furthering understanding of the role of *deposition on snow and ice*. Such data could be used to inform climate models and verify impacts.

6. Continued investigation of the differential toxicity of PM components and mixtures and the shape and magnitude of the PM health impact function.

A great deal of research on the health impacts of $PM_{2.5}$ and specific PM components has been conducted over the past 15 years, and these topics have already been identified as priorities by EPA in the context of its periodic reviews of the U.S.

national ambient air quality standards for PM. While the scientific record is robust in many respects, there are still important unanswered questions about the relative toxicity of different constituents. Also, research continues to inform the overall understanding of the magnitude and nature of PM health impacts, including more precise quantitative information about the relationship between indoor and ambient concentrations and health impacts. Continued investment in this research is important, and there is a particular need for more studies in developing countries.

7. More detailed analysis and comparison of the costs and benefits of mitigating BC from specific types of sources in specific locations.

More work is needed to link BC sources in specific regions to climate, health and environmental impacts, all the way through the causal chain. Improved characterization of BC control strategies, their costs, and their net impact on radiative forcing, as influenced by location, will help ensure maximum climate benefits. This depends in large part on improved *emissions characterization and measurement*, as described above, but also more refined modeling techniques capable of evaluating regional or local scale impacts. Greater attention should be paid to the location of the proposed change in emissions, especially for near-Arctic or near-Himalayan emissions. Similarly, the links between *non-radiative impacts of BC, such changes in rain, snow, and water resources*, and specific source classes or regions have not yet been well established; the ability to relate non-radiative effects to aerosol (and precursor) emissions needs further development.

Health impacts will also vary by source type and location. As discussed above, more work on PM components is need and this can support further analysis to help identify emissions reductions with maximum co-benefits for public health and climate. While the relationship between BC and visibility is relatively well understood, the *impacts of BC dimming on other welfare outcomes, such as ecosystem and crop health*, have not been well quantified. Research on the human health and environmental consequences of reductions in specific sectors, coupled with development of appropriate metrics (#8, below) would allow for comparison between source sectors and regions and improved ability to develop and meet policy goals.

8. Refinement of policy-driven metrics relevant for BC and other short-lived climate forcers.

Some of the fundamental assumptions that go into the calculation of policy-relevant climate metrics for long-lived GHGs do not apply to BC; therefore, it is difficult to apply metrics developed for GHGs to BC and other short-lived forcers. Though "alternative" metrics have been proposed for BC, none is yet widely utilized. Appropriately tailored metrics for BC are needed in order to quantify and communicate BC's impacts and properly characterize the costs and benefits of BC mitigation. Improved metrics could incorporate non-radiative impacts of BC, such as impacts on precipitation. Similarly, given BC's (and other aerosols') direct impacts on human health, health outcomes could also be incorporated into such a metric. Developing methods to quantify the benefits of BC mitigation on both climate and health would encourage policy decisions that factor in climate and health considerations simultaneously, within a unified framework. Analysis is also needed to examine how utilizing alternative metrics would affect policy priorities and preferred mitigation options.

9. Analysis of key uncertainties.

Systematic analysis of key remaining uncertainties and technical gaps regarding BC could help prioritize future research and investment by clarifying which of these factors exert the largest influence on modeled outcomes. Such analysis would involve both: (1) Model intercomparison of BC radiative forcing and climate impacts between global and regional models, along with comparisons to ambient measurements (including remote sensing and tracer-based analyses); and (2) Sensitivity analysis of the factors influencing models' representation of (a) the net effect of a given mitigation measure, considering all co-emitted pollutants; and (b) the overall global and regional contribution of BC and OC to radiative forcing and temperature change.

Global and regional models give a different range of predictions of BC's RF and climate impacts due to different model configurations, parameterizations and assumptions (model resolution, chemical and physical processes, aging/mixing, deposition, etc.). A comparison of model results and diagnostic analysis will reduce remaining uncertainties regarding BC impacts. Additional sensitivity analysis should consider the importance of: (1) emissions inventories utilized (including type and magnitude of co-emissions represented); (2) model representation of transport and vertical distribution of emissions, aging and mixing of particles, radiative properties of particles, and particle interactions with clouds and snow; and (3) the use of observational data to constrain model results and emissions estimates.