Appendix 7

Research Needs

The chapters of this report have laid out much of what is known about BC. While there is a great body of knowledge about BC, its emissions, its atmospheric properties, its effects on climate, and its impacts on health, more information on these topics would lead to enhanced capability to design policies and control strategies that would be most beneficial for the environment and for human health. Many of these research priorities have been highlighted in this report; these research needs are summarized here, with the relevant section(s) of the report calling for each research topic given in parentheses. These descriptions also give more detail on the uncertainties and research needs discussed in sections **12.5** and **12.6**.

A7.1 Basic Atmospheric Chemistry of BC, LAC, and Measurement Approaches

Establishing standardized definitions of terms related to carbonaceous aerosols and harmonizing measurement approaches will reduce the uncertainty in emissions inventories and result in improved and more consistent air quality and climate estimates. Standardized definitions will also encourage the use of preferred monitoring approaches and more consistent, less uncertain data, resulting in better climate and health assessments; currently, a lack of consistency in connections between BC and health endpoints could be caused by uncertain or inconsistently produced data. These definitions can provide the basis for future reference and equivalent measurement methods for a regulatory program if ever needed.

- It is important to develop standardized definitions of BC, BrC, non-light-absorbing OC and other light-absorbing aerosols (**2.3**).
- It is also important to establish corresponding reference materials for needed particle properties (**2.3**, **5.2**).
- Interpretation and harmonization of existing ambient and emissions measurements are necessary to conform to the specified definitions and properties to meet the needs of climate and health assessments (**5.2**).

While BC absorbs light across the entire solar spectrum, BrC absorbs primarily in the ultraviolet range. The quantity of solar energy absorbed depends upon the molecular structure and the mass of the relevant BrC compounds present in a combustion plume or aerosol mixture. OC is usually the most significant co-emitted pollutant, by mass, among the major BC emitting sources.

- Estimates are needed to separately characterize BrC and the non-light-absorbing (scattering) portions of OC. Characterizations of the particulate, semi-volatile and perhaps some volatile ("intermediate VOC") components of non-light-absorbing (scattering) portions of OC are especially important to improve inventories, to improve model estimates of SOA, and to evaluate models.
- It is necessary to develop and/or improve instrumentation and measurement techniques to identify and quantify the physical and chemical properties (optical, size, number, composition, and mass) of BrC and LAC, and through modeling, to estimate the radiative forcing of BrC.
- It is also important to develop the ability to track the radiative forcing and cloud droplet-forming potential of particles, from various emissions sources, as they age in the atmosphere (**5.2, 2.6**).

There is also a need to improve instrumentation and measurement techniques to identify and quantify the properties of BC (optical, size, number, and mass) taking into consideration different emissions sources, combustion conditions and varying particle mixtures (**5.2**, **4.3**, **4.4**). Further study is needed to understand the differences among existing thermal and optical monitoring and measurement methods for BC and how they are affected by (a) the emissions sources and resulting aerosol mixtures (considering variations in the combustion process and different fuels for source measurements), (b) atmospheric processing (aging), and (c) the manner in which monitoring is performed. Preferred protocols for future measurements and monitoring are desired to ensure more consistent and useful data collection. Improved source measurement techniques will facilitate the opportunity for more measurements, better emission factors and then better inventories. Multiple methods may be needed to serve different data needs.

A7.2 Ambient and Emissions Source Measurement

Emissions source measurements are much more limited than ambient measurements. Additional representative source measurements are needed to better characterize BC emissions (and speciated profiles) by emissions source, fuel type and combustion conditions. These data are needed to improve BC emission factors and inventories, to create BrC emission factors and inventories, and to help develop emissions and modeling uncertainties. Research can also help guide a new focused data collection effort.

- Methods for using source measurements to develop emission factors for light-absorbing carbon (including BrC) – particularly for the major source categories like open biomass combustion and mobile sources – need to be explored (5.2, 4.3, 4.4).

Regular speciated PM measurements, including EC (or BC) measurements, currently occur at very coarse spatial and temporal scales. More spatially dense ambient monitoring can help identify unaccounted for emissions and sources. More temporal estimates (within and among years) as well as semi-continuous data will help account for the impacts of emissions trends. Understanding the effect of historical emissions changes will be useful in estimating the need for future emissions reductions to meet various policy goals.

- More ground-level ambient measurements are needed, with improved spatial and temporal coverage, particularly outside the United States. These data would be useful for a multitude of reasons, including better understanding of pollution trends and better linkages between PM components, such as BC, and health, climate, ecosystem, and visibility outcomes (**5.3**, **5.4**, **and 5.7**).

A consolidated global database of BC and OC ambient and source measurements would be useful for facilitating the analysis of all existing data and for ensuring consistent development of inventories and evaluation of global climate models. A protocol should be established to improve the quality and to guide the reporting of meta-data available both for ambient measurements and source profiles (e.g. identifying conversions of absorption measurements to mass and adjustments for sampling artifacts and or material balance). Consistent reporting of measurements is desired because the variability among existing measurement approaches and data contribute to the uncertainty of domestic and global emissions estimates and impacts.

- Mechanisms for archiving, consolidating, and sharing existing measured data on light absorption and scattering of particles, available globally, are needed to reduce the need for new measurements and to produce better air quality and climate characterizations (**5.2**, **5.7**).

Full chemical composition emissions measurements for the important carbonaceous combustion sources, including the identification of carbonaceous co-pollutants in addition to BC (OC, BrC) measurements would promote better understanding the atmospheric aging and climate-relevant properties of carbonaceous aerosols as well as would be essential in constructing the emissions inventories needed for assessment of any co-benefits and tradeoffs from BC mitigation efforts (**5.2**, **4.3**, **4.4**, **6.4**).

A7.3 Emissions Inventories

A7.3.1 Global

Given the importance of emissions inventories in understanding the impacts of BC and control measures, more accurate representations of BC emissions globally is critical for more accurate estimates of BC's impacts. Sources of BC outside the United States are responsible for 94% or so of the current emissions globally and this number is expected to increase in the future. The work of Bond et al. (i.e., 2004) is widely recognized as the "best currently available" global BC inventory. That work is based on combinations of fuel, combustion type, and emissions controls and their prevalence on a regional basis. The 2004 work (which represented 1996 fuel-use data) has since been updated to reflect more recent years and to improve the emission factors and usage patterns for some sources. However, there remain significant uncertainties for BC inventories in developing countries and globally. There are several ways in which these inventories can be improved. Suggested areas for further research largely focus on improving these emissions by gathering more data both on the emissions side and on the “usage” (activity level) side as well on determining how best to allocate these emissions both spatially and temporally:

- For mobile sources, there is a need to better characterize the on-road and nonroad fleet in urban and rural areas for different countries including commercial marine and locomotives.
- Emissions estimates for nonroad applications need to be developed and collated separately from on-road operations (**4.4.1**).
- In the case of biomass burning, all fires need to be better captured for their emissions characteristics and activity level.
- A careful review of usage patterns needs to be conducted to ensure that appropriate “activity” levels are applied to emission factors to arrive at final emissions estimates (**4.4.3**).
- Small(er) sources are especially poorly represented on a regional basis, and better characterization of emissions from residential cookstoves, in-use mobile sources, small fires, smaller industrial sources such as brick kilns, and flaring emissions is needed.
  - Many of these “small” sources could have relatively high BC emission factors (**4.4.1** and **4.4.3**).
  - 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.
- Steps need to be taken to better engage international scientists, governments, and regulatory agencies in collaborations of technology assessments to help improve base-year and out-year global emissions.
  - Merging regional inventories with global estimates should be explored in an attempt to improve country- and region-specific emissions estimates in global inventories (**4.4.3** and **4.4.4**).
  - Initiating an international forum in which scientists and governments can more readily and routinely engage to help facilitate and share this research would expedite emissions inventory improvement and help to harmonize estimation methods across world regions.

A7.3.1.1 Domestic

While domestic emissions of BC and PM are generally better characterized than global emissions, considerable uncertainty remains for these estimates and there are several aspects of domestic inventories that need improvement.

- 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, most likely through increased testing and data acquisition. (These needs are all discussed in Section **4.3.2**.)
  - Special attention should be given to PM mass and composition from nonroad sources (gasoline and diesel), aircraft (including in-flight emissions), commercial marine especially C3 (ocean going), and locomotives including both current and, where available, future technologies.
  - Characterization of emissions from newer-technology on-road diesel and gasoline vehicles would also be useful, as would better emissions characterization (including fleet fraction) of high-emitting vehicles/engines (so-called “super-emitters”).
  - Finally, the improved characterization of emissions at low ambient temperature and with different fuels (including renewables) would improve the understanding of present and future emissions from mobile sources.

These data can then be used to develop newer and more accurate emission factors for these key areas within mobile sources. These new data could also enable construction of emissions models specifically for EC for nonroad sources similar to what exists for on-road (and rely less on using $PM_{2.5}$ models and translating to EC via a separate database in which speciated emissions from sources are archived).

A7.3.2 Uncertainty Analysis

For both global and domestic EC/BC emissions, analyses of uncertainty would aid in determining which sectors have the strongest estimates of BC emissions, which in turn could lead to easier decisions on mitigation options. Bond et al. (2004) have done a Monte Carlo-type uncertainty analysis for global emissions and have estimated that uncertainty in BC emissions inventories is generally on the order of a "factor of 2," and more work along these lines is needed. A starting point on the domestic side would be to qualitatively rank sources by considering the strengths and weaknesses of how the BC emissions were assembled. This could lead to a research task of doing a more rigorous uncertainty analysis on the global estimates. This method could also be applied to future-year projections of emissions.

- Quantitative measures for describing uncertainties in emissions should be advanced, as was suggested in Section **4.4.4**.
- As a first step, a qualitative description of uncertainty in emissions estimates, sector-by-sector, for domestic emissions inventories including models should be performed.
- The uncertainty that stems from combining BC data sets collected by several measurement techniques (for regional and global inventories) should be estimated.
- Finally, the Monte Carlo-type work by Bond et al. (2004) should be extended to determine uncertainties in global emissions estimates.

A7.4 Ambient Observations, Including Deposition

While many kinds of additional measurements would improve our understanding of BC in the atmosphere, a few specific types of measurements were highlighted in this report as able to fill some important gaps in the current understanding of BC. BC's vertical distribution (and its impact on surface and atmospheric radiative forcing and cloud formation) is one of the important uncertainties in assessing BC's overall impact. Similarly, the deposition of BC is a source of uncertainty in determining BC's overall impacts. For example, a recent NOAA/GFDL modeling study (Liu et al., 2011) showed that the simulated vertical column of BC concentrations over the Arctic is highly sensitive to different parameterizations of deposition properties.

- Better characterizing the vertical distribution of BC would allow for a fuller understanding of its climatic impacts, which are dependent on its vertical distribution, and would further understanding of the discrepancies between models and observations (**5.5** and **5.7**).
- Research to inform the characterization of BC wet scavenging and dry deposition rates, deposition on snow and ice and resulting radiative forcing, albedo, and hydrological changes (**2.6**, **5.6.2**, **5.6.5**) would improve the modeling of these important processes.

A7.5 Modeling

Some aspects of the modeling of BC in the atmosphere, and its effects on climate, are better understood than others. BC's aging/mixing states (internal, external, or core-shell) and its indirect and semi-direct effects are likely the largest uncertainty in assessing BC's RF and climate impacts.

- Improving the modeling of BC's direct effects due to aging/mixing states assumptions, semi-direct effects (on vertical mixing, clouds, and differential heating at surface and the atmosphere), and indirect effects (on cloud formation, lifetime, albedo, etc.) would be very useful for improving representations of BC's environmental impacts (**2.6**).

BrC is also a heretofore under-studied aspect of the impacts of carbonaceous aerosols. Inclusion of BrC in climate models, and analysis of implications for net forcing, including a sensitivity analysis of the upper and lower reasonable bounds for BrC absorption, would enable a fuller accounting of the climatic impacts of carbonaceous aerosol sources.

- Reporting column data by wavelength may aid model-observation comparison as BC and BrC differ in terms of peak absorption (**2.3**, **5.6.2**).
- Coupled with experimental estimates of BrC emissions and laboratory estimates of BrC scattering and absorption, this should clarify the magnitude of the cooling offset due to organic carbon co-emissions, which is important for determining net forcing of abatement measures.

A7.6 Climate Impacts

Further research on the impacts of BC and carbonaceous aerosols on climate, with an eye toward filling in the continuum from source to impact, would enable policies that are more likely to have beneficial impacts. Several aspects of this issue were highlighted in the chapters of this report. Emissions of other pollutants from the same sources can lead to difficulties in determining whether a control strategy will result in radiative cooling or warming. In addition, there are indications that near the Arctic and other snow-covered regions, the net effect of any mitigation measure including measurable amounts of BC is much more likely to be net cooling.

- Better characterization of the sources as well as the "total" radiative effect of the control measure will reduce the possibility of unintentional warming as well as lead to more efficient policy.
- Research is needed to characterize the range of possible control strategies and evaluating the probability that a given measure will result in net cooling (**6.4**). Specific focus should be placed on the location (especially latitude) of the proposed change in emissions, especially for near-Arctic emissions. Specific measures would be the goal, but sectorial-level analysis would also be useful.

One important aspect of BC's impacts on climate is its role in snow and ice melting. This is of particular relevance in areas where BC deposition may affect snow pack that influences the availability of water resources for downstream populations (e.g., California, Himalayas and Tibetan Plateau, Andes, high African mountains) as well as in the Arctic. Focused research on the role of deposited BC could shed light on the effectiveness of mitigation measures for protecting water resources and snow in sensitive regions.

Specific contributors to the overall uncertainty in BC's impacts include aerosol mixing state and cloud impacts. The biggest uncertainty in direct effect calculations is due to aging/mixing of particles, and the biggest uncertainty overall may be cloud interactions. Continued research is needed on the radiative properties of BC and co-emissions, especially regarding cloud interactions and effects of aging/mixing (**2.6**).

Non-radiative impacts of BC are more poorly understood than its radiative impacts; even if the net radiative effect of a given measure is near-zero, there may be other climatic impacts. Continued research is needed on the non-radiative effects of BC and other aerosols, especially regarding precipitation/hydrological interactions and dimming (**2.6.3**).

A7.7 Metrics

It is difficult to apply climate metrics developed for GHGs to BC and other short-lived forcers as many of the fundamental assumptions that go into the calculation of these policy-relevant metrics for long-lived GHGs are not appropriate for application to BC. 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.

Ways to quantify the various impacts of BC into a unified framework or to compare BC to other SLCFs and GHGs would enable quantification of how BC mitigation leads to the attainment of various policy goals:

- Explore the use of emissions source measurements and/or emissions inventory estimates to determine whether (or how) measures like OC/EC ratios, BC (as measured currently), and other LAC forms can be utilized to inform development of metrics to prioritize emissions sources for mitigating the climate effects of PM emissions (**5.2, 2.7.3**). Simple emission-related measures are useful screening tools that permit mitigation decisions without the need to run complex climate models. Currently, such measures are used but with unknown, but probably large, uncertainty. For example, using directly emitted OC as an indicator of scattering from aerosols does not acknowledge the role of SOA or OC's BrC component.
- There is a need for an analysis of the implications of using different metric choices on future emissions and climate, examining the benefits of near-term versus long-term temperature abatement and therefore short-lived vs. long-lived gas abatement (**2.7.3, 2.7.4**). One example of this would be a system where an economic model is run with different GWP/GTP values

for BC, and then the emissions are fed into a climate model. Key issues involve the relationship between different metrics values and economic impacts, and in terms of the temporal pattern of temperature implications.

- Given the differences in the mechanisms by which BC and GHGs impact climate and human health, there is a need for improved quantification and valuation of specific climate change impacts that could be attributed to BC emissions, including analysis of how these differ from quantification of GHG reduction benefits.

- Additionally, development of approaches to identify and properly account for co-benefits in mitigation benefit analyses would more accurately capture the climatic impacts of policy options (**2.7.3, 2.7.4**). Key differences between BC and other GHGs for valuation purposes include the regional specificity of BC impacts, the differences in vertical distribution of forcing, and cloud interactions. Human health effects and precipitation, visibility, and dimming effects are also cited as benefits of BC control. Including these benefits could improve metrics development and would move these metrics beyond simply climatic endpoints to a whole host of environmental and health goals.

A7.8 Health

A great deal of research on the health impact 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.

In addition to the ongoing research on the health impacts of PM components such as BC, work is needed on linking the many types of impacts from a particular emissions sector. Research is needed to quantify the integrated climate and health impacts of individual economic sectors and domestic and international mitigation measures, accounting for the full mixture of emissions, both direct and indirect climate effects, and both indoor and outdoor exposure (**2.7.3.5, 2.7.4**, **3.3**, and **3.4**). This includes the complex mix of organic compounds that comprise the co-emitted species from BC sources such as fossil fuel and biomass combustion. This would help elucidate where the greatest opportunities to benefit human health and the environment lie, with respect to BC mitigation.

A7.9 Mitigation Technologies and Measurements

Of key importance is research on which BC mitigation strategies are most cost-effective and beneficial for public health and climate. The necessary continued research on mitigation includes more information on costs and benefits of mitigation by sector, and development of new or improved mitigation technologies for various sectors. This research would in turn allow for comparisons across sectors in terms of costs and benefits for climate and human health. The following research needs are for specific source sectors.

A7.9.1 Stationary

While emissions from controlled domestic sources are relative well understood, there are ways in which estimates could be improved. Additional source testing and development of improved emission factors (**9.8**) would result in higher quality emissions inventories for stationary sources in the developed and the developing world. This would improve our estimates of the effectiveness of traditional control equipment (baghouses, electrostatic precipitators) in reducing the BC fraction of PM. Along with improved activity level estimates, it would improve overall emissions inventory estimates for the industrial sector. Key categories would include coke production, brick kilns, and oil and gas flaring. Profiles for stationary sources in the developing world are especially uncertain.

A7.9.2 Mobile

Mobile sources, especially on an international basis, are an important source of EC emissions and improved, more effective, and more cost-effective control technology would result in wider adoption and likely benefits for both human health and climate change mitigation. It is important to continue the development of current mobile source control technology (such as diesel particulate filters for in-use vehicles) targeted specifically for EC, including the ability to assure adequate durability and lower costs. Also, the applicability to more existing engines, especially nonroad, locomotive, and C1/C2 marine, is needed. Control technology for C3 marine is also needed. The speciated emissions profiles that result from the use of existing control technologies are currently not well characterized (**8.6**).

A7.9.3 Cookstoves

Given the ubiquity of high-emitting cookstoves in the developing world, it is not surprising that there are many opportunities for research into mitigating cookstove emissions. First, linking cookstoves to climate outcomes requires a clear understanding of the emissions from particular stoves and fuels. Currently, such information is lacking, and most of the testing that is occurring is in laboratory settings. Therefore, there is a need for laboratory and field testing to characterize emissions (BC, OC, CH_4, other constituents) from different types of cookstoves, based on stove design, fuel type, and usage patterns (**10.4.1**, **10.4.2**). Expanded lab and in-field testing data are needed to clarify what constitutes a "clean" stove/fuel.

Because of the difference in fuels among regions, as well as the difference in sensitivity of the local and regional environment to climate forcers, there is a need for regional-level studies of the net climate impacts of cookstove emissions from different cooking stove-fuel combinations, including linkages to radiative forcing, glacial melt, and precipitation impacts (**10.4.1, 10.4.2**). Studies evaluating the extent to which emissions from stoves are linked to climate impacts at the local/regional level would help clarify which cookstove mitigation efforts would be beneficial for climate, and what technologies and fuels would be needed to achieve maximum climate benefits.

In order to make good policy decisions about preferred interventions and investments, there is need to better understand the linkages between emissions changes and health benefits. Improved dose/response information would enable policymakers to target specific improved stoves and fuels for development and dissemination. Specifically, research is recommended on examining dose-response relationships between emissions of various cookstove emission constituents and health endpoints of concern (ALRI/pneumonia, COPD, cardiovascular disease, cancer, etc.) (**10.4.1**, **10.4.2**).

A7.9.4 Residential Heating

There are some uncertainties associated with the emissions from residential heating. More research on the composition of particles from residential heating (**10.3.1**) would enable better quantification of the benefits of mitigation from the residential sector. More data on the optical properties of these aerosols would be especially useful. Related to this uncertainty in emissions composition is the effect that different heating technologies and abatement options have on the chemical composition of carbonaceous aerosol emissions (**10.3.1**). There is currently little data on whether the improved stoves used for air quality purposes equally reduce all PM components, or whether some are reduced preferentially. These changes in composition can be measured using existing (or new) techniques for emissions speciation.

Similarly, the performance of residential heating appliances as they age has not been well documented. Given that the lifetime of wood stoves is on the order of several decades, more complete long-term performance data on the emissions from older heating appliances would enable more accurate emissions and impact projections into the future (**10.3.2**).

A7.9.5 Biomass Burning

Globally, a major fraction of BC emissions come from biomass burning, and yet biomass burning emissions are especially uncertain. In order to understand the efficacy of mitigation options, biomass burning emissions should be better characterized. Specifically, there is a need for additional measurements and biomass burning emissions and activity factors as a function of size and duration of the fire, fuel type, fuel conditions, fire phase, and meteorological conditions on the day of the burn and other significant variables (**11.3**). There is a need for more information about total area burned in each fire category in the United States and globally, and also a need for additional fire activity data on a broad scale. A complete impacts assessment of biomass combustion emissions requires inventories that include both BC and BrC, along with co-pollutants that may offset warming, and other materials that are implicated in human health and ecosystems impacts. More information on the plume rise of such fires would also improve their representation in chemical transport models.

Regarding actual mitigation measures for biomass burning, there is a need for an analysis of the efficacy of existing and proposed methods, including analysis of total life-cycle impacts. An assessment of the efficacy, and any unintended consequences due to the implementation, of proposed measures for biomass smoke mitigation, beginning with a synthesis of available research results (**11.5.1**, **11.6**) would be especially useful in considering mitigation options. This type of analysis could conceivably include (1) total life-cycle studies of mitigation methods, both individually and in combination with others, for ecosystems impacts, (2) total life-cycle studies of the net climate forcing impacts arising from the use of these methods, or (3) total life-cycle studies of the economic impacts of the use of these methods.