Chapter 1

Introduction

Black carbon (BC) has recently received a great deal of attention among scientists and policymakers for its impacts on global and regional climate. Though substantial and immediate reductions in long-lived greenhouse gases (GHG) are essential for solving the problem of climate change over the long term, BC offers a promising mitigation opportunity to address climate effects in the near-term and to slow the rate of climate change. BC's high capacity for light absorption and its role in key atmospheric processes link it to a range of climate impacts, including increased temperatures, accelerated ice and snow melt, and disruptions in precipitation patterns. BC is also a constituent of fine particles ($PM_{2.5}$) and is therefore associated with an array of respiratory and cardiovascular health impacts. This makes it ripe for emissions reduction approaches that bring both climate and public health benefits.

Like many air pollutants, BC's atmospheric fate is affected by a number of complex physical and chemical processes that may enhance or attenuate BC's warming impacts. Some of these atmospheric processes are not yet completely understood, making it challenging to represent them accurately in climate models and to project future impacts. Furthermore, BC is always co-emitted with other pollutants, many of which have offsetting climate impacts. Thus, BC must be studied in the context of the total emissions mixture coming from particular sources. In its 2007 Fourth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) noted that the climate effects of particles remained "the dominant uncertainty" in estimating climate impacts (IPCC, 2007). Since that time, additional research has helped to reduce this uncertainty, through inventory improvements, advances in measurement technologies and methods, and increasing sophistication in the representation of particle atmospheric chemistry in climate models. Thus, though important uncertainties remain, substantial progress has been made in understanding the role of BC and other particles in climate processes. Recent work has clarified BC's climate effects and the emissions control approaches necessary to mitigate these impacts.

To further efforts to understand the role of BC in climate change, on October 29, 2009, the United States Congress established requirements for the U.S. Environmental Protection Agency (EPA) to conduct a BC study as part of *H.R. 2996: Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010*. Specifically, the legislation stated that:

> *"Not later than 18 months after the date of enactment of this Act, the Administrator, in consultation with other Federal agencies, shall carry out and submit to Congress the results of a study on domestic and international black carbon emissions that shall include*
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> - *an inventory of the major sources of black carbon,*
> - *an assessment of the impacts of black carbon on global and regional climate,*
> - *an assessment of potential metrics and approaches for quantifying the climatic effects of black carbon emissions (including its radiative forcing and warming effects) and comparing those effects to the effects of carbon dioxide and other greenhouse gases,*
> - *an identification of the most cost-effective approaches to reduce black carbon emissions, and*
> - *an analysis of the climatic effects and other environmental and public health benefits of those approaches."*

To fulfill this charge, EPA has conducted an intensive effort to compile, assess, and summarize available scientific information on the current and future impacts of BC, and to evaluate the effectiveness of available BC mitigation approaches and technologies for protecting climate, public health, and the environment. The results are presented in this *Report to Congress on Black Carbon*. This report has been peer reviewed by a special panel of experts appointed under the Council on Clean Air Compliance Analysis, a Federal Advisory Committee chartered under the Federal Advisory Committee Act (FACA), 5 U.S.C., App 2. The Black Carbon Review Panel concluded that "the draft report is comprehensive and well-written; summarizes relevant scientific literature; and successfully convey[s] a wealth of complex information" (Pope, 2011). This final report reflects numerous additions and improvements suggested by the peer review panel. In addition, the final report reflects input from other federal agencies, many of which have a great deal of expertise in this area and a range of programs relevant to BC. As requested by Congress, EPA has consulted with these other federal agencies while developing this report, and has incorporated material supplied by the agencies into key sections of the Report, including chapters on emissions inventories, health and climate science, and sector-specific mitigation options.

1.1 Key Questions Addressed in this Report

In evaluating the climate impacts and mitigation opportunities for BC, it is essential to recognize from the outset that BC presents a different kind of climate challenge than CO_2 and other long-lived GHGs. BC's short atmospheric lifetime (days to weeks) and heterogeneous distribution around the globe result in regionally concentrated climate impacts. Thus, the location of emissions releases is a critical determinant of BC's impacts, which is not the case for long-lived and more homogeneously distributed GHGs like CO_2. The composition of the total emissions mixture is also key: since many co-emitted pollutants such as sulfur dioxide, oxides of nitrogen, and most organic carbon particles tend to produce a cooling influence on climate, the amount of BC relative to these other constituents being emitted from a source is important. Furthermore, BC is linked to a whole variety of effects beyond warming. These include the darkening of ice and snow, which reduces reflectivity and accelerates melting; changes in the formation and composition of clouds, which affect precipitation; and impacts on human health.

These key characteristics of BC give rise to some important questions addressed in this Report, including:

1. What is BC, and how does it lead to climate warming?

2. What is the net effect of atmospheric BC on global and regional temperature change in terms of both magnitude and time scale?

3. What is known about the magnitude of BC's effect on snow and ice, and its impacts on precipitation?

4. What is known about BC's contribution to $PM_{2.5}$-related human health impacts and other, non-climate environmental impacts?

5. What kind of real-world BC data exists from monitoring networks and other observational research?

6. How large are U.S. and international emissions of BC currently, which sectors are the main contributors, and how are emissions projected to change in the future?

7. What is the potential value of BC reductions as a component of a broader climate change mitigation program, taking into account both co-pollutant emissions reductions and the public health co-benefits?

8. What specific considerations will determine preferred mitigation strategies in different national and regional contexts?

9. What technologies and approaches are available to address emissions from key sectors, and at what cost?

10. Which mitigation options represent potential top-tier opportunities for key world regions, including the United States?

In answering these questions, this Report focuses on synthesizing available scientific information about BC from peer-reviewed studies and other technical assessments, describing current and future emissions estimates, and summarizing information on available mitigation technologies and approaches, including their costs and relative effectiveness. Given the number of recent studies and the limited time available to complete this Report, EPA did not seek to undertake extensive new analysis (such as climate modeling of specific BC mitigation strategies), but instead relied on information available in the literature. The report focuses on BC, where the bulk of scientific research is available, but acknowledges the potentially important role played by other light-absorbing particles which are still subject to great uncertainty. This Report also describes specific research and technical information needed to provide a stronger foundation for future decision-making regarding appropriate and effective BC mitigation policies.

1.2 Other Recent Assessments of BC

Numerous international and intergovernmental bodies, including the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), the Convention on Long Range Transboundary Air Pollution (CLRTAP), and the Arctic Council, have identified BC as a potentially important piece of the climate puzzle. Each of these bodies has recently prepared an assessment of BC that included consideration of the impacts of BC on climate, the potential benefits to climate of reducing BC emissions, and/or the mitigation opportunities that appear most promising. These assessments have identified a number of additional actions—from improvements in inventories to evaluation of specific mitigation opportunities—that could be taken to help gather further information about BC and address emissions from key sectors.

In the *Integrated Assessment of Black Carbon and Tropospheric Ozone* (UNEP and WMO, 2011a), UNEP/WMO conclude that BC mitigation may offer near-term climate benefits. This study was designed to assess the role of BC and ozone in climate and air quality, and to recommend mitigation measures that could be expected to provide benefits in both the climate and air quality arenas. Out of roughly two thousand potential mitigation measures, the UNEP/WMO analysis has identified a small subset of measures as providing the largest mitigation potential. The *Assessment* finds that full implementation of the targeted measures (which included methane reductions for ozone mitigation, as well as BC reductions) could greatly reduce global mean warming rates over the next few decades. Specifically, the analysis suggests that warming anticipated to occur during the 2030s based on emissions projections could be reduced by half through application of these BC and methane measures. In contrast, even a fairly aggressive strategy to reduce CO_2 would do little to mitigate warming over the next 20-30 years. The UNEP/WMO *Assessment* concludes that while CO_2 measures clearly are the key to mitigating long-term climate change out to 2100, BC and methane measures could reduce warming and slow the rate of change in the next two decades. The *Assessment* also recognizes the substantial benefits to air quality, human health, and world food supplies that would result from reductions in BC and tropospheric ozone.

The CLRTAP Ad-hoc Expert Group on Black Carbon and the Arctic Council Task Force on Short-Lived Climate Forcers focused mainly on identifying high-priority mitigation options and the need for supporting information, such as national BC emissions inventories. These groups did not conduct independent scientific assessments; rather, after a review of existing scientific literature, they concluded that current evidence suggests that BC plays an important role in near-term climate change. The CLRTAP Ad-hoc Expert Group was co-chaired by the United States and Norway. In its final report presented to the Convention's Executive Body in December 2010, the Expert Group highlighted key findings, including:

- There is general scientific consensus that mitigation of BC will lead to positive regional impacts by reducing BC deposition in areas with snow and ice.
- There is virtual certainty that reducing primary PM will benefit public health.
- The Arctic, as well as alpine regions, may benefit more than other regions from reducing emissions of BC.
- Climate processes unique to the Arctic have significant effects that extend globally, so action must be taken in the very near term to reduce the rate of warming.
- Impacts on the Arctic and alpine areas will vary by country, but all countries will benefit from local emissions reductions of BC and other co-emitted pollutants.

The Expert Group concluded that because of the public health benefits of reducing BC, as well as the location of the countries across the Convention regions in relation to the Arctic, the Executive Body should consider taking additional measures to reduce BC. The report included information about key sectors and emphasized the need to develop emissions inventories, ambient monitoring and source measurements in an effort to improve the understanding of adverse effects, efficacy of control measures and the costs and benefits of abatement. Based in part on the findings of the Expert Group, the CLRTAP Executive Body decided to include consideration of BC as a component of PM in their ongoing process of revising the Gothenburg Protocol.[1] This decision marks the first time an international agreement has attempted to address the issue of short lived climate forcers in the context of air pollution policy. Revisions to the Gothenburg Protocol are expected to be completed in 2012.

The Arctic Council Task Force on Short-Lived Climate Forcers was formed following the issuance of the

[1] The Protocol to Abate Acidification, Eutrophication and Ground-level Ozone was adopted in Gothenburg, Sweden in 1999. See *http://www.unece.org/env/lrtap/multi_h1.html*.

Tromsø Declaration at the Arctic Council Ministerial in April 2009.[2] This declaration formally noted the role that short-lived forcers may play in Arctic climate change, and recognized that reductions of emissions of these compounds and their precursors have the potential to slow the rate of Arctic snow, sea ice, and sheet ice melting in the near term. The Task Force, which is being co-chaired by the United States and Norway, is charged with identifying existing and new measures to reduce emissions of short-lived climate forcers (BC, ozone and methane) and recommending further immediate actions that can be taken. The Task Force focused its initial efforts on BC, and presented a menu of mitigation options to Arctic Nations at the Arctic Council Ministerial in May of 2011 (Arctic Council, 2011). The key findings of this Task Force include:

- Addressing short-lived climate forcers such as black carbon, methane and ozone offers unique opportunities to slow Arctic warming in the near term.
- Black carbon emitted both within and outside of the Arctic region contributes to Arctic warming. Per unit of emissions, sources within Arctic Council nations generally have a greater impact.
- Controls on black carbon sources that reduce human exposure to particulate pollution improve health, and in that regard many measures can be considered no regrets.
- To maximize climate benefits, particulate matter control programs should aim to achieve maximum black carbon reductions.

In making these recommendations, the Task Force recognized that not all measures to control ambient PM necessarily reduce BC, and encouraged countries to consider BC-focused strategies as a complement to existing PM control programs in order to ensure climate as well as health and environmental benefits. Based on its findings, the Task Force recommended that Arctic Council nations take action to reduce BC, and laid out a menu of specific mitigation options in key sectors such as land-based transportation, stationary diesel engines, residential wood combustion, agricultural and forest burning, and shipping. The Task Force has also encouraged Arctic nations to develop and share domestic inventories of BC emissions, which can be used to further define—and refine—global inventories.

The Task Force is collaborating with the Arctic Monitoring and Assessment Programme (AMAP) working group, which established an Expert Group on Short-Lived Climate Forcers to prepare a detailed technical report, *The Impact of Black Carbon on Arctic Climate*. This report (Quinn et al., 2011) contains climate modeling results highlighting the significance of BC emissions sources from different sectors and different regions for the Arctic climate. The AMAP report indicates that emissions both from within the Arctic and from the rest of the world affect Arctic warming, with sources near to or within the Arctic having particularly significant impacts per unit of emissions.

These concurrent international assessments strongly suggest that reducing BC emissions will slow the rate of warming and provide other near-term benefits to climate, as well as protect public health. The analyses conducted in support of these assessments provide useful information to clarify BC's role in climate change, the impact of key emissions source categories, and the applicability of different mitigation options. This *Report to Congress on Black Carbon* builds upon these efforts, summarizing and incorporating their key findings as appropriate. Since all of the efforts mentioned above have been conducted by international bodies with a focus outside the United States, readers are encouraged to read their final reports and recommendations as additional sources of information.

1.3 Organization of this Report

This Report is organized into twelve chapters and seven technical appendices. Each of the chapters that follow this *Introduction,* and the appendices, are described briefly below:

Chapter 2 describes how particles, including BC, absorb and scatter light, and identifies the factors that influence the direction and magnitude of their effect on the Earth's climate. The chapter defines "black carbon," describes how BC relates to other types of particles, and discusses how these substances affect climate. Next, the chapter provides detailed information on the range of direct and indirect impacts of BC on global and regional climate. It summarizes available estimates of BC's global and regional radiative forcing and related temperature effects, snow and ice albedo effects, cloud effects, and precipitation effects.

[2] The Arctic Council comprises the eight member states with land above the Arctic Circle (Canada, Denmark including Greenland and the Faroe Islands, Finland, Iceland, Norway, Russian Federation, Sweden, and the U.S.), six permanent participants representing indigenous peoples resident in those member states, and a number of observers. The Council does not have legally-binding authority over its members, but rather promotes cooperation, coordination, and interaction regarding common Arctic issues.

The chapter also considers how best to compare the effects of BC to the impacts of other climate forcers, particularly CO_2. It evaluates the applicability of traditional metrics developed for CO_2 to BC, and presents alternative metrics designed specifically for evaluating the climate impacts of short-lived climate forcers like BC.

Chapter 3 outlines EPA's current scientific understanding of the health and non-climate environmental effects of BC. This chapter discusses the large body of scientific evidence regarding the adverse human health impacts of $PM_{2.5}$ in general, and provides a summary of health research related to BC as a component of the overall $PM_{2.5}$ mix. It also describes BC's role in visibility impairment and ecological effects.

Chapter 4 provides a detailed look at BC emissions inventories. The chapter characterizes current (2005) U.S. emissions of BC by source category, and provides detailed information regarding emissions from sectors that are the most significant contributors to U.S. emissions, such as mobile sources, open biomass burning, and stationary fossil fuel combustion. The chapter also provides an overview of global and regional emissions inventories for BC, and contrasts these global inventories with more refined regional inventories available for some areas, such as the United States, China and India. Special attention is paid to emissions near the Arctic. The chapter discusses the transport of emissions from particular sources and regions, and describes historic emissions trends.

Chapter 5 summarizes key findings from observational data on BC. This includes data from ambient air quality monitors, ice/snow cores, and remote sensing. The chapter describes the existing BC monitoring networks, and summarizes available data regarding ambient levels in urban and rural areas, both domestically and globally. The chapter also describes trends in ambient BC concentrations.

Chapter 6 considers the potential climate and human health benefits of BC emissions reductions. The chapter describes the findings of existing studies on the global and regional benefits of BC mitigation, including specific strategies aimed at reducing emissions from key sectors. The chapter acknowledges the large remaining uncertainties with regard to evaluating the climate benefits of BC mitigation in some sectors, but notes that controls on BC and co-emitted pollutants are generally associated with significant public health benefits, through reductions in $PM_{2.5}$ and its precursors. The chapter also discusses approaches for valuing health and climate impacts.

Chapter 7 provides a framework for evaluating mitigation options. The chapter describes the different considerations, including benefits, costs, technologies, and other factors that affect decisionmaking, and the impact of these considerations on choices among BC mitigation options. It provides some illustrative examples of which mitigation options might be preferred depending on the weight policymakers assign to different factors in the mitigation framework.

Chapters 8-11 describe existing control programs and technologies that have been demonstrated to be effective in reducing BC emissions from source categories of regional and/or global importance. These include **Mobile Sources** (Chapter 8), **Stationary Sources** (Chapter 9), **Residential Heating and Cooking** (Chapter 10), and **Open Biomass Burning** (Chapter 11). For each sector, the chapter recaps current and projected emissions estimates (accounting for control programs currently in place but not yet implemented), describes key control technologies and other mitigation strategies that can help control BC emissions from specific source types, and provides available information regarding control costs. The chapters also discuss how alternative strategies, such as changes in land-use policy or energy systems, could impact emissions from the sectors. Control options, costs, and known or potential barriers to mitigation are described separately for U.S. domestic emissions and international emissions. In some cases, there are considerable differences in mitigation approaches, cost, and feasibility between the United States and other countries. Also, there are gaps in available information on these factors for many sectors.

The conclusion, **Chapter 12**, focuses on identifying important BC mitigation opportunities for the United States and other world regions. Drawing on earlier chapters and the findings of other recent assessments, this chapter clarifies some of the key mitigation options that can clearly be expected to provide near-term climate and health benefits. The chapter acknowledges the diversity of approaches for BC mitigation and the need to tailor mitigation strategies to specific national and local contexts. The chapter also identifies key gaps in current scientific understanding, and provides a list of high-priority research needs. Additional research in these areas is essential for improving the current scientific understanding of the impact of BC and other light-absorbing particles on climate, and for estimating the full impact of mitigation approaches in different sectors and regions on both climate and public health. These research needs may stimulate further work on BC by EPA and other organizations.

Appendix 1 provides further details regarding alternative definitions of BC and other light-absorbing particles, and the techniques and instruments used for ambient monitoring and measurement of BC.

Appendix 2 provides a detailed explanation of the methods that are used to compile U.S. emissions inventories for BC. It also further explores the variety of global and non-U.S. regional emissions inventories available and some of the key differences among those inventories.

Appendix 3 summarizes the results of available studies which have estimated the public health benefits that might accrue from alternative BC mitigation strategies, at either the global or regional level.

Appendix 4 describes world-wide efforts to reduce the sulfur content of diesel fuels, which is an important prerequisite to reducing BC emissions from mobile sources.

Appendix 5 provides a full list of the emissions standards for different categories of mobile sources in the United States, and the emissions limits set under those standards.

Appendix 6 describes existing emissions standards for heavy-duty diesel vehicles internationally, and the anticipated schedule for emissions reductions resulting from these standards.

Appendix 7 discusses a variety of research needs related to BC. Though the highest priority research needs are discussed in Chapter 12, this appendix provides more detail regarding specific gaps in the currently available information on BC that are important both from a scientific perspective and for informing BC mitigation decisions.