

Table of Contents

Acknowledgments	i
Highlights	iii
List of Figures	xii
List of Tables	xxi
List of Acronyms	xxiii
Glossary	xxviii
Executive Summary	1
Chapter 1 Introduction	11
1.1 Key Questions Addressed in this Report	12
1.2 Other Recent Assessments of BC	13
1.3 Organization of this Report	14
Chapter 2 Black Carbon and Its Effects on Climate	17
2.1 Summary of Key Messages	17
2.2 Introduction	18
2.3 Defining Black Carbon and Other Light-Absorbing PM	20
2.4 Key Attributes of BC and Comparisons to GHGs	25
2.5 The Role of Co-Emitted Pollutants and Atmospheric Processing	28
2.6 Global and Regional Climate Effects of Black Carbon	32
2.6.1 Global and Regional Radiative Forcing Effects of BC: Overview	33
2.6.2 Impact of BC Radiative Forcing on Temperature and Melting of Ice and Snow	47
2.6.3 Other Impacts of BC	49
2.6.4 BC Impacts in the Arctic	52
2.6.5 BC Impacts in the Himalayas	55
2.6.6 Summary of BC Impacts in Key Regions	56
2.7 Metrics for Comparing Black Carbon Impacts to Impacts of Other Climate Forcers	56
2.7.1 Metrics along the Cause and Effect Chain	57
2.7.2 Commonly-Used Metrics for GHGs	59
2.7.3 Applicability of Climate Metrics to BC	61
2.7.4 Using Metrics in the Context of Climate Policy Decisions	64
2.8 Key Gaps in Understanding and Expressing the Climate Impacts of BC	66

Chapter 3 Black Carbon Effects on Public Health and the Environment 67

3.1 Summary of Key Messages. 67

3.2 Introduction 67

3.3 Health Effects Associated with BC. 67

 3.3.1 Key Health Endpoints Associated with Exposure to PM 67

 3.3.2 Health Effects Related to Ambient BC Concentrations 69

 3.3.3 Health Effects Related to Indoor BC Exposures. 81

3.4 Non-Climate Welfare Effects of PM_{2.5}, Including BC 82

 3.4.1 Role of BC in Visibility Impairment 82

 3.4.2 Role of BC in Crop Damage and Other Environmental Impacts 83

3.5 Key Uncertainties Regarding Health/Environmental Impacts of BC 83

Chapter 4 Emissions of Black Carbon. 85

4.1 Summary of Key Messages. 85

4.2 Introduction 85

4.3 U.S. Black Carbon Emissions 86

 4.3.1 Summary of Emissions Methodology 86

 4.3.2 U.S. Black Carbon Emissions: Overview and by Source Category 87

4.4 Global Black Carbon Emissions 95

 4.4.1 Summary of Global Black Carbon Emissions by Region and Source Category. 96

 4.4.2 Black Carbon Emissions North of the 40th Parallel 104

 4.4.3 Alternative Estimates of Global and Regional Emissions 106

 4.4.4 Inventory Comparisons for U.S. Black Carbon Emissions 107

4.5 Long-Range Transport of Emissions. 109

4.6 Historical Trends in Black Carbon Emissions 112

 4.6.1 U.S. Black Carbon Emissions Trends. 112

 4.6.2 Global Black Carbon Emissions Trends 112

Chapter 5 Observational Data for Black Carbon 115

5.1 Summary of Key Messages. 115

5.2 BC and Other Light-Absorbing Carbon: Measurement Methods 116

5.3 Ambient Concentrations of BC 118

 5.3.1 Major Ambient Monitoring Networks. 118

 5.3.2 Global Ambient Concentrations. 119

 5.3.3 Comparison of Urban and Rural Concentrations Globally 119

 5.3.4 BC as a Percentage of Measured Ambient PM_{2.5} Concentrations
 in the United States 123

5.4 Trends in Ambient BC Concentrations. 125

 5.4.1 Trends in Ambient BC Concentrations in the United States
 and the United Kingdom 125

 5.4.2 Trends in Ambient BC Concentrations in the Arctic 128

5.5 Remote Sensing Observations 129

5.6 BC Observations from Surface Snow, Ice Cores, and Sediments	132
5.6.1 Measurement Approach	132
5.6.2 Surface Snow Data.	132
5.6.3 Ice Core Data.	134
5.6.4 Sediment Data	135
5.6.5 Arctic BC Snow and Ice Data – Source Identification	136
5.7 Limitations and Gaps in Current Ambient Data and Monitoring Networks	137
Chapter 6 Benefits of Reducing Black Carbon Emissions	139
6.1 Summary of Key Messages.	139
6.2 Introduction	140
6.3 Public Health Benefits of Reducing Black Carbon Emissions	140
6.3.1 Health Benefits in the United States	140
6.3.2 Global Health Benefits	144
6.3.3 Conclusions Regarding Potential Health Benefits	148
6.4 Climate Benefits of Reducing Black Carbon Emissions	148
6.4.1 Studies Estimating Physical Climate Benefits	149
6.4.2 Comparing Climate Benefits of Reductions in BC vs. CO ₂	154
6.4.3 Valuing the Climate Benefits of BC Mitigation	156
6.4.4 Conclusions Regarding Climate Benefits	158
6.5 Environmental Benefits of BC Reductions.	159
6.5.1 Visibility Impacts.	159
6.5.2 Ecosystem Impacts.	159
6.5.3 Materials Co-benefits	160
6.5.4 Conclusions Regarding Environmental Benefits	160
6.6 Conclusions.	160
Chapter 7 Mitigation Overview: Designing Strategies for Public Health and Near-Term Climate Protection	161
7.1 Summary of Key Messages.	161
7.2 Introduction	162
7.3 Effect of Existing Control Programs	162
7.4 Future Black Carbon Emissions	163
7.5 Key Factors to Consider in Pursuing BC Emissions Reductions	166
7.5.1 Defining Goals: Climate, Health and Environmental Outcomes	167
7.5.2 Identifying Opportunities for Emissions Reductions	168
7.5.3 Key Considerations.	169
7.6 Applying the Mitigation Framework.	172
7.7 Conclusions.	173
Chapter 8 Mitigation Approaches for Mobile Sources	175
8.1 Summary of Key Messages.	175
8.2 Introduction	176

Table of Contents

8.3 Emissions Trajectories for Mobile Sources 176

8.4 New Engine Standards in the United States. 177

 8.4.1 On-road and Nonroad Diesel Engines 180

 8.4.2 On-road and Nonroad Gasoline Engines 182

 8.4.3 Other Mobile Sources – Commercial Marine Vessels, Locomotives, and Aircraft . 183

8.5 New Engine Standards Internationally. 184

 8.5.1 International Regulations of Diesel Fuel Sulfur Levels 184

 8.5.2 Standards for New Engines Outside the United States. 185

8.6 Mitigation Approaches for In-use Mobile Sources in the United States 186

 8.6.1 Available Retrofit Technologies and Strategies for In-use Engines. 187

 8.6.2 Cost-Effectiveness of Retrofits 190

 8.6.3 Applicability of Diesel Retrofits 191

 8.6.4 Experience with Diesel Emissions Reduction Programs in the United States . . . 191

8.7 Mitigation Approaches for In-use Mobile Engines Internationally 194

Chapter 9 Mitigation Approaches for Stationary Sources 195

 9.1 Summary of Key Messages. 195

 9.2 Introduction 195

 9.3 Emissions from Key Stationary Source Categories 196

 9.4 Available Control Technologies for Stationary Sources 197

 9.4.1 Fabric Filters 197

 9.4.2 Electrostatic Precipitators 198

 9.4.3 Diesel Particulate Filters and Oxidation Catalysts 198

 9.5 Cost-Effectiveness of PM Control Technologies. 199

 9.6 Mitigation Approaches Other than PM Control Technologies 200

 9.6.1 Process Modification/Optimization 200

 9.6.2 Fuel Substitution and Source Reduction Approaches for PM 200

 9.7 Mitigation Approaches for Stationary Sources Internationally 201

 9.7.1 Brick Kilns. 201

 9.7.2 Coke Production/Iron and Steel Production 202

 9.7.3 Power Generation and Industrial Boilers 202

 9.7.4 Oil and Gas Flaring. 203

 9.8 Technical and Research Needs. 203

Chapter 10 Mitigation Approaches for Residential Heating and Cooking. 205

 10.1 Summary of Key Messages 205

 10.2 Introduction. 206

 10.3 Residential Wood Combustion in Developed Countries. 207

 10.3.1 Emissions from Residential Wood Combustion 207

 10.3.2 Approaches for Controlling Emissions from RWC 207

 10.3.3 Emissions Standards for New Wood-burning Units 208

 10.3.4 Mitigation Opportunities for In-Use RWC Sources 209

 10.3.5 Additional Regulatory Approaches to Limiting Wood Smoke Emissions 211

10.3.6	Wood Smoke Reduction Resource Guide	212
10.4	Residential Cookstoves in Developing Countries	213
10.4.1	Emissions from Cookstoves	214
10.4.2	Technologies and Approaches for Controlling Emissions from Cookstoves	214
10.4.3	Programmatic Considerations for Cookstove Mitigation	221
Chapter 11	Mitigation Approaches for Open Biomass Burning	227
11.1	Summary of Key Messages	227
11.2	Introduction.	227
11.3	Emissions from Open Biomass Burning	227
11.4	Fire as a Resource Management Tool	229
11.5	Smoke Mitigation Technologies and Approaches in the United States	230
11.5.1	Managing Smoke	231
11.5.2	Fire Prevention Techniques.	233
11.6	Mitigation Technologies and Approaches Globally	234
Chapter 12	Key Black Carbon Mitigation Opportunities and Areas for Further Research	237
12.1	Summary of Key Messages	237
12.2	Introduction.	238
12.3	Controlling Black Carbon as Part of Broader PM _{2.5} Mitigation Program	239
12.4	Key Black Carbon Mitigation Opportunities	240
12.4.1	U.S. Black Carbon Mitigation Opportunities.	241
12.4.2	Global Black Carbon Mitigation Opportunities	242
12.4.3	Other Mitigation Options	245
12.5	Key Policy-Relevant Scientific Uncertainties	245
12.6	High Priority Research Needs for Black Carbon	247
Appendix 1	Ambient and Emissions Measurement of Black Carbon.	251
Appendix 2	Black Carbon Emissions Inventory Methods and Comparisons.	271
Appendix 3	Studies Estimating Global and Regional Health Benefits of Reductions in Black Carbon.	285
Appendix 4	Efforts to Limit Diesel Fuel Sulfur Levels	287
Appendix 5	U.S. Emission Standards for Mobile Sources	295
Appendix 6	International Emission Standards for Heavy-Duty Vehicles	299
Appendix 7	Research Needs	303
Bibliography	311

List of Figures

Figure A.	BC Emissions by Major Source Category.	2
Figure B.	Regional Variability in Direct Radiative Forcing and Snow/Ice Albedo Forcing for BC from All Sources.	3
Figure C.	BC Emissions, 2000, Gg.	5
Figure D.	Policy Framework for Black Carbon Mitigation Decisions.	7
Figure 2-1.	Effects of BC on Climate, as Compared to GHGs.	19
Figure 2-2.	BC Images.	20
Figure 2-3.	Representative Examples of Filter Samples Collected from Different Sources.	21
Figure 2-4.	Light Absorption by BC, BrC, and Ambient Mixtures.	22
Figure 2-5.	TEM Image of a BrC Particle.	24
Figure 2-6.	Coarse Urban PM (Diameter > 2.5 microns) with a Black Surface Coating.	24
Figure 2-7.	Climate Response to Emissions of Pollutants with Different Lifetimes.	28
Figure 2-8.	Projected Global Mean Temperatures under Various Scenarios Relative to the 1890-1910 Average.	29
Figure 2-9.	Particle Transformation in the Atmosphere, from Point of Emission to Deposition.	30
Figure 2-10.	Components of Global Average Radiative Forcing for Emissions of Principal Gases, Aerosols, and Aerosol Precursors, based on IPCC estimates.	34
Figure 2-11.	Estimates of Radiative Forcing from BC Emissions Only.	35
Figure 2-12.	Estimates of Direct Radiative Forcing from BC Emissions Only.	37
Figure 2-13.	Direct Radiative Forcing ($W m^{-2}$) of BC from All Sources.	38
Figure 2-14.	Estimates of Snow and Ice Albedo Radiative Forcing Effects from BC Emissions Only.	41
Figure 2-15.	Snow and Ice Albedo Forcing by BC.	42
Figure 2-16.	Estimates of Direct Radiative Forcing from OC Emissions Only.	43
Figure 2-17.	Estimates of Direct Radiative Forcing from BC and OC Emissions.	43
Figure 2-18.	Direct Forcing by OC from All Sources.	44
Figure 2-19.	Global Radiative Forcing Due to Perpetual Constant Year 2000 Emissions, Grouped By Sector, at (a) 2020 and (b) 2100 and Showing the Contribution from Each Species.	45
Figure 2-20.	Spatial Distribution of Change in Mean Snow Water Equivalent (SWE, mm) for March.	48
Figure 2-21.	BC Concentrations in the ZD Glacier.	49
Figure 2-22.	Surface Dimming by Anthropogenic Aerosols ($W m^{-2}$).	51
Figure 2-23.	Evidence of Arctic Ice Melt.	53
Figure 2-24.	Cause and Effect Chain from Emissions to Climate Change, Impacts, and Damages.	57
Figure 2-25.	Ranges and Point Estimates for Regional Estimates of GWP Values for One-Year Pulse Emissions of BC for Different Time Horizons.	62
Figure 2-26.	Ranges and Point Estimates for Regional Estimates of GTP Values for One-Year Pulse Emissions of BC for Different Time Horizons.	63

Figure 3-1.	Conceptual Diagram of the Epidemiological Evidence for the Association of BC with the Continuum of Cardiovascular Effects.	76
Figure 4-1.	BC and OC Fractions of PM _{2.5} Emissions for the Highest BC Emitting Non-Mobile Source Categories in the United States.	86
Figure 4-2.	Heavy-Duty Diesel PM _{2.5} Emissions Profile.	87
Figure 4-3.	Contribution to Primary PM _{2.5} , BC, and OC Emissions by Mega Source Categories.	88
Figure 4-4.	U.S. BC Emissions (tons) for Major Source Categories.	89
Figure 4-5.	U.S. BC Emissions from all Mobile Source Categories.	92
Figure 4-6.	U.S. BC Emissions from all Biomass Combustion Source Categories (250,000 short tons).	94
Figure 4-7.	Acres Burned per Year in Alaskan Wildfires, 2002-2010.	95
Figure 4-8.	Global BC Emissions based on Year 2000 Estimates, in Gigagrams (Gg).	97
Figure 4-9.	BC Emissions (Aggregate) by Selected World Region, 2000 (Gg).	97
Figure 4-10.	Global Distribution of BC and OC Emissions by Major Source Category.	102
Figure 4-11.	BC Emissions by World Region, 2000 (Gg).	103
Figure 4-12.	Global BC Emissions by Source Categories and Region.	104
Figure 4-13.	Geographical Distribution of Global BC Emissions by Latitude.	105
Figure 4-14.	Comparison of Regional Inventories for China, India, and Indonesia with AR5 Estimates.	107
Figure 4-15.	Relative Importance of Different Regions to Annual Mean Arctic BC Concentrations at the Surface and in the Upper Troposphere (250 hPa).	110
Figure 4-16.	Potential for Transport of U.S. Emissions to the Arctic.	111
Figure 4-17.	Historical Growth in Emissions of BC and OC, Segregated by Fuel and World Region.	113
Figure 4-18.	Historical Reconstruction of Global Emissions Trends.	113
Figure 4-19.	BC Emissions (Tg /y) in the United States, United Kingdom, and China.	114
Figure 5-1.	Measurement of the Carbonaceous Components of Particles.	117
Figure 5-2.	Ambient BC Measurement Locations Worldwide.	119
Figure 5-3.	Spatial Distribution of Global BC Data.	121
Figure 5-4.	Annual Mean BC Concentrations ($\mu\text{g m}^{-3}$) for 2005–2008 in the United States.	122
Figure 5-5.	Urban BC Gradients for New York City.	123
Figure 5-6.	Composition of PM _{2.5} for 15 Selected Urban Areas in the United States.	124
Figure 5-7a.	Trends in Black Smoke Measurements ($\mu\text{g}/\text{m}^3$) in the United Kingdom, 1954-2005.	124
Figure 5-7b.	Comparison of Ambient Black Smoke Measurements ($\mu\text{g}/\text{m}^3$, annual average) with Estimated BC emissions (Tg) in the United Kingdom, 1955-2000.	124
Figure 5-8.	Ambient BC Trends in Washington, D.C.	125
Figure 5-9.	Trends in BC at All IMPROVE Network Stations with Sufficient Data between 1 March 1990 and 29 February 2004.	126
Figure 5-10.	Estimated Annual Average Ambient BC Concentrations in the San Francisco Bay Area vs. Diesel Fuel Consumption.	127
Figure 5-11.	Ambient BC Trends in Boston (Harvard School of Public Health location).	127
Figure 5-12.	Ambient BC Trends (2002-2010) in the United States.	128
Figure 5-13.	The Annual Mean BC Concentrations Measured at Alert (a), Barrow (b), and Zeppelin (c) and Split into Contributions from the Four Transport Clusters.	129
Figure 5-14.	Aerosol Absorption Optical Depth (AAOD) from AERONET (1996–2006) and OMI (2005–2007).	130

List of Figures

Figure 5-15.	Absorption Angstrom Exponent (AAE) Values for AAOD Spectra Derived from AERONET Data.	130
Figure 5-16.	AERONET AOD and AAOD as a Percentage of AOD.	131
Figure 5-17.	Locations of BC Measurements in Surface Snow and Shallow Snow Pits.	133
Figure 5-18.	BC Concentrations in Surface Snow in Arctic and Subarctic Areas of the Northern Hemisphere.	133
Figure 5-19.	BC Ice Core Records Worldwide Labeled by Their Identifying Name.	134
Figure 5-20.	Atmospheric BC determined by Husain et al. (2008), for the Adirondack Region from 1835 to 2005.	135
Figure 5-21.	Annual Average Concentrations of (a) BC and VA and (b) BC and Non-Sea-Salt Sulfur (nss-S).	136
Figure 5-22.	Sources of BC in Arctic Snow.	137
Figure 6-1.	Estimated Global Mortality Benefits of Black Carbon Reductions.	145
Figure 6-2.	Annual Avoided Premature Cardiopulmonary and Lung Cancer Deaths Per Unit BC Emissions Reduced versus Total BC Emissions (Gg) for Particular Source Sectors within Each Region.	146
Figure 6-3.	Comparison of Premature Mortality by Region (millions of premature deaths annually).	147
Figure 6-4.	Global Radiative Forcing Due to Perpetual Constant Year 2000 Emissions, Grouped by Sector, in 2020 and 2100.	150
Figure 6-5.	Observed Deviation of Temperature to 2009 and Projections under Various Scenarios.	151
Figure 6-6.	Summary of Normalized Net Forcing per Unit of Emissions.	152
Figure 6-7.	Contribution to Radiative Forcing of Carbonaceous Aerosol Emissions within Different Latitude Bands.	153
Figure 6-8.	Integrated Forcing by Aerosols Emitted from Burning 1 Kg of Fuel from Different Sources.	155
Figure 6-9.	Cause and Effect Chains for (a) CO ₂ and (b) BC from Emissions to Damages.	157
Figure 7-1.	Global BC Emissions Forecasts for Various Sectors under Alternative IPCC SRES Scenarios (in teragrams (Tg) of carbon).	164
Figure 7-2.	Black Carbon Emissions Growth, 2000-2030 under IPCC A1B Scenario.	165
Figure 7-3.	Future Emissions of BC under IPCC Representative Concentration Pathways, 2000-2050 (Gg/year).	165
Figure 7-4.	Policy Framework for Black Carbon Mitigation Decisions.	167
Figure 7-5.	OC (left) and BC (right) Emissions from Key U.S. and Global Emissions Source Categories, Expressed as a Fraction of Total Carbon (OC + BC) Emissions from that Category.	170
Figure 8-1.	Estimated Changes in Emissions of (a) BC, (b) OC, and (c) Direct PM _{2.5} from Mobile Sources in the United States, 1990-2030.	179
Figure 10-1.	OC/BC Emission Ratios by Source Category and Fuel Type.	208
Figure 10-2.	Cost Per Ton PM _{2.5} Reduced for Replacing Non-EPA-Certified Wood Stove with EPA-Certified Woodstove (in 2010\$).	210
Figure 10-3.	Cost Per Ton PM _{2.5} Reduced (\$/Ton) for the Addition of an Insert into a Fireplace (2010\$).	211
Figure 10-4.	The Turbococina Stove.	215
Figure 10-5.	Woman Prepares Banku on a BioLite HomeStove in Kintampo, Ghana.	215
Figure 10-6.	CleanCook Ethanol Stove.	216

Figure 10-7.	Charcoal Stoves.	217
Figure 10-8.	Philips Woodstove (forced draft) Manufactured in Lesotho.	218
Figure 10-9.	Rocket Stoves.	219
Figure 10-10.	Prakti Double-Pot Woodstove with Chimney.	220
Figure 10-11.	Number of Improved Stoves Sold by PCIA Partners, 2003-2010.	222
Figure 10-12.	Potential Growth in the Number of Households Adopting Clean Cookstoves Globally through 2020.	224
Figure 12-1.	Key Policy-Relevant Scientific Uncertainties Related to BC.	246

List of Tables

Table 2-1.	Comparison of BC to CO ₂ on the Basis of Key Properties that Influence the Climate.	26
Table 2-2.	Examples of Particle Types and Mixtures Present in Combustion Plumes.	31
Table 2-3.	Summary of UNEP/WMO Assessment Estimates of Radiative Forcing Effects of BC.	36
Table 2-4.	Overview of the Different Aerosol Cloud Effects.	39
Table 2-5.	Overview of the Different Aerosol Indirect Effects and Their Implications for Global Dimming and Precipitation.	50
Table 2-6.	Arctic Temperature Impacts from Emissions of BC from Different Sectors.	54
Table 2-7.	Climate Effects of BC in the United States, Asia, and the Arctic (Summary).	56
Table 2-8.	Examples of Commonly Used Metrics for GHGs.	58
Table 3-1.	Summary of Causal Determinations for Exposure to PM _{2.5} from 2009 PM ISA.	68
Table 3-2.	Summary of Epidemiological Studies of BC and Cardiovascular Health Outcomes.	70
Table 3-3.	Summary of Epidemiological Studies of BC and Respiratory Health Outcomes.	77
Table 3-4.	Summary of Epidemiological Studies of BC and Mortality.	79
Table 4-1.	2005 U.S. Emissions (tons) and Ratios of Emissions by Mega Source Category.	89
Table 4-2.	U.S. Emissions of PM _{2.5} , BC, and OC (short tons).	90
Table 4-3.	National Level U.S. Emissions of PM _{2.5} , BC, and OC for Biomass Combustion Sources in 2002/2005 (short tons).	94
Table 4-4.	Global BC Emissions in 2000 (in Gg). Transport Includes Aircraft and Shipping.	98
Table 4-5.	Global OC Emissions in 2000 (in Gg). Transport Includes Only Aircraft.	100
Table 4-6.	OC/BC Ratios by Broad Source Categories.	103
Table 4-7.	A Comparison of BC Emissions Nationally to Those from Sources “North of 40 th Parallel” in 2005 (short tons).	106
Table 4-8.	Comparison of BC and OC Emissions (in Gg) for the United States between AR5 Global Inventories and EPA Inventories.	108
Table 5-1.	Description of BC Measurement Techniques.	116
Table 5-2.	Summary of Selected Global BC Ambient Concentrations for Urban and Rural/Remote Areas.	120
Table 6-1.	PM _{2.5} Health Endpoints Included in EPA’s Regulatory Impact Analyses.	141
Table 6-2.	Changes in Key Health Effects Outcomes in the United States Associated with PM _{2.5} Resulting from the 1990 CAA Amendments.	142
Table 6-3.	List of Benefits, Costs, and Benefit to Cost Ratios for U.S. Rules with Direct PM Reductions (Billions 2010\$).	142
Table 6-4.	Direct PM _{2.5} National Average Benefits per Ton Estimates by Source Category for the United States (3% Discount Rate, Thousands of 2010\$).	143
Table 8-1.	Mobile Source BC, OC, and PM _{2.5} Emissions 1990-2030 (short tons).	178
Table 8-2.	Cost Estimates for Particulate Matter Controls on New Diesel Engines (2010\$), based on Recent U.S. EPA rulemakings.	182
Table 9-1.	PM Control Costs for ICI Boilers.	200
Table 11-1.	Types of Open Biomass Burning.	228