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Black Carbon and Climate Change

Considerations for International Development Agencies

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Preface

Over the past decade black carbon has come to be seen as a major agent contributing to global warming. Emissions of black carbon come from all countries, but developing countries play a particular role since some emissions are closely associated with poverty and with the process of economic development. These include black carbon from the transport sector and from use of biomass and coal in the rural residential sector. As an element of particulate matter pollution black carbon has already attracted much attention from development practitioners, due to the severe effects of such pollution on public health. Climate change thus brings a new global environmental dimension to a well-known local environmental and health problem.

The scientific understanding of the role of black carbon in climate change has lagged behind that for carbon dioxide and other greenhouse gases. The gap appears to be closing as research is expanding rapidly. Yet as this basic paper seeks to describe, the scientific challenges to quantifying the contribution of black carbon to climate change remain significant. However, this should not inhibit policy preparation and consideration of black carbon in development work.

This paper aims to provide an overview of this important topic for development practitioners, and suggests some considerations for integrating the impact of black carbon on climate into broader development policy. It is not a detailed scientific review, nor does it cover all aspects of this multifaceted issue. The aim is to introduce the topic to development specialists working in climate change policy, and in the many sectors where black carbon is an issue, including transport, energy, urban development, rural development, and public health.

As evidence of the mounting importance of this topic, the link between black carbon and climate change is the subject of a rapidly growing number of publications among climate change research and policy groups. While this paper focuses on material published until the end of 2010, it makes note of further key reports released prior to publication.

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Acronyms and Abbreviations

ABC	Atmospheric brown cloud
BC	Black carbon
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
DPF	Diesel particulate filter
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquified petroleum gas
OECD	Organisation for Economic Co-operation and Development
PM	Particulate matter
RF	Radiative forcing
SLCF	Short-Lived Climate Forcers
SO_2	Sulfur dioxide
ULSD	Ultra-low sulfur diesel
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
W/m^2	Watts per square meter

Executive Summary

This report is intended to inform the international development community about the links between black carbon and climate change. With growing scientific clarity on the contribution of black carbon to climate change, the benefits of limiting its emissions are becoming more evident. This report reviews the existing knowledge on the subject and identifies relevant considerations for development organizations.

What is Black Carbon?

Black carbon (BC) consists of extremely small particles that result from the incomplete combustion of fossil fuels and biomass. Commonly known as soot, it is one of the many types of particulate matter (PM, also called aerosols) that influence the climate; the others include sulfates and volcanic ash. Over the past decade, BC has come to be recognized as one of the principal agents of global warming. Climate science now views BC as the second or third largest warming agent after carbon dioxide (CO_2), alongside methane.

The primary emissions sources of BC include burning of agricultural land and forests (both human-induced burning and natural burning), use of biomass for fuel (wood, charcoal, and so forth), coal use in households and industry, and use of diesel for transportation and stationary power generation. In large power stations using coal, the PM is almost always filtered out from emissions.

The average lifetime of BC particles in the atmosphere is one to two weeks, compared with millennia for a significant fraction of CO_2 emissions. Hence BC, unlike CO_2, does not accumulate from year to year; instead it is constantly replenished by the human and natural activities of the previous few weeks.

What is Known About the Impact of Black Carbon on the Climate?

BC warms the atmosphere differently than greenhouse gases (GHGs). It is highly effective in absorbing energy from the sun, which the particles then convey to the atmosphere. It also darkens snow and ice, causing them to warm and melt more rapidly. The melting usually reveals darker land or sea, making the Earth's surface less reflective, which amplifies global warming. Increasing evidence indicates that BC is a major cause of the rapid warming and melting of snow and ice in the Arctic and the Himalayas. In addition to the direct effect on atmospheric warming, BC and other aerosols have large indirect effects on the global climate through their complex influence on clouds and precipitation. Moreover, particles undergo chemical changes after they are emitted. Calculation of the net impact of these direct and indirect effects must take into account their interactions and various feedback mechanisms. Such calculations are done using global climate models of increasing sophistication. Scientific understanding of how the multiple actions of BC affect the climate is far from complete and is less comprehensive than for the GHGs. Considerable research is being carried out in this area, with rapid progress being made.

BC is emitted with organic carbon particles, which tend to condense into gray or white PM (that is, smoke) that can reflect sunlight back into space, thus exerting a cooling influence on the climate. While black smoke has a high proportion of BC and exerts a strong warming influence, white smoke contains mostly organic carbon and so exerts a cooling influence. For example, open burning of biomass creates near-white smoke and thereby exerts a large net cooling influence. Use of biomass for cooking creates varieties of gray smoke that may have either a net warming or net cooling influence. In contrast, diesel engines and coal combustion create almost black smoke that is strongly warming.

Because it consists largely of BC, cutting PM from diesel and coal is highly likely to reduce global warming; however, in the case of open burning and biomass from cooking stoves, cutting PM may not always lead to a net reduction in global warming, because cooling from lower BC emissions is offset by the reduction in cooling (that is, increase in warming) from lower emissions of organic carbon. When looking at the net climatic impact of changing an activity, such as biofuels burning, all of the co-emissions of gases and PM from the activity need to be considered.

Along with other aerosols and short-lived gases (for example, ozone), BC was not included in the Kyoto Protocol. This is partly because of the limited scientific understanding at the time of the contribution of BC to climate change. In addition, estimating the volumes of emissions of BC is difficult, as they come from a very large number of sources and processes. Due to its short atmospheric lifetime, BC is not uniformly mixed in the atmosphere, and its concentrations can vary regionally, preventing the straightforward global atmospheric sampling done for measuring the volumes of GHGs. Moreover, the impacts of BC are regional as well as global, unlike the Kyoto gases where the impacts are almost entirely global. Emissions estimates indicate that the mass of BC emitted from developed countries has been decreasing as burning of biomass has declined and coal and diesel emissions controlled. In developing countries, BC emissions are rising, although the rate of growth is likely to decline as incomes rise further in the coming decades.

Why Reduce Emissions of Black Carbon?

Since its substantial role in global warming is becoming clearer, BC is becoming more prominent in global strategies to address climate change. Climate models show that a rapid reduction in BC emissions would reduce their warming influence over the ensuing months roughly in proportion to the amount of BC in the atmosphere. In theory, the elimination of all BC emissions from the global atmosphere could postpone exceeding the threshold of dangerous warming by one or two decades. In practice, however, it is not possible to reduce BC emissions selectively; any policy cutting BC emissions would also reduce emissions of cooling organic carbon. It should be emphasized that tackling BC emissions alone will not solve the basic problem of climate change, which is caused by the long-term accumulation and persistence of the climate effects of CO_2 and other GHGs.

In addition to causing global warming, BC has substantial effects on the regional climate. In areas with high emissions of BC, the resulting extensive brown haze can affect temperature and precipitation. Early evidence is suggesting that large BC emissions in India and China have caused shifts in the Indian monsoon and in Chinese rainfall patterns. The impact of BC on ice and snow, and hence on water accumulation, is becoming increasingly important in assessing the total effect of climate change in the Arctic and the Himalayas. In these regions, the specific local effects of BC add to the impact of global warming, causing temperatures to rise much more rapidly than the global average. At the regional level, organic carbon does not offset the effects of BC, and all sources of BC emissions, including biomass burning, contribute to BC's net climatic impacts.

The adverse health impacts of inhaling BC, which are similar to those caused by other small PM, are well understood. The widespread use of biomass and coal for cooking in developing countries makes PM, including BC, one of the leading causes of death and disease, with about 2 million premature deaths a year from damage to the respiratory organs. PM from diesel engines and industrial coal use also damages health significantly. To date all interventions that reduce BC have been done as part of a program to limit health damage from PM. Because the environmental consequences of emissions of BC are both local (health) and global (climate change), dealing with BC can provide a good example of co-benefits from environmental policies. Reducing PM from diesel and coal clearly benefits health, reduces perturbations in regional climates, and reduces global warming; reducing PM from biomass burning clearly benefits health, reduces perturbations in regional climates, and may also reduce global warming.

Challenges Ahead

The policy priorities for dealing with the effects of human-induced BC emissions on climate require careful consideration. These need to address both the challenges of reducing PM emissions overall and the different impacts of lower PM emissions from various activities. Thus, cutting PM from diesel and coal will reduce global warming due to the high proportion of BC in emissions. But cutting PM from biomass burning (open burning and cooking) will have less certain impacts on climate because of the need to take into account the offsetting impact of BC and organic carbon. Climate science is still evolving, and its messages for policy may change.

In the short run, large-scale global mitigation of BC emissions is still challenging in many respects. The technologies to reduce PM, including BC, are well known. They are being introduced in high-income countries, where they will eventually lead to reduced BC emissions. The introduction of these technologies in developing countries will require new policy initiatives and substantial investment. For diesel, large capital expenditures will be needed in refineries to produce ultra-low sulfur diesel (ULSD) that permits removal of PM from vehicle emissions. Even when such diesel is available, vehicles must possess the advanced technology to cut PM emissions, such as vehicle particle traps. Introducing advanced biomass cookstoves to poor rural households in developing countries in order to cut PM emissions has taken much longer than expected, due to the difficulty of overcoming a range of local economic, social, and technical barriers. Cooking with clean petroleum fuels is not affordable for most low-income households, and the priority has been to introduce improved cookstoves, of which a wide range are available.

Many studies have detailed the costs and benefits on health grounds of reducing emissions of PM, which includes BC. However, there has been limited analysis that also takes into account the climate impact of BC and organic carbon emissions. Calculating the overall economic costs and benefits of mitigating BC involves assessing impacts in multiple areas, including health, and both regional and global climate impacts. Much work remains to be done in this area and there is significant potential for advancing understanding. Improved data on BC and organic carbon emissions is much needed, particularly for biomass cooking.

Considerations for the Future

Development agencies deal with activities that can generate or reduce BC in developing countries, directly or indirectly. Since BC has significant environmental consequences, understanding these is important for the agencies' operations and policies.

Agencies could consider addressing BC emissions in a number of ways:

- ***Mainstream consideration of BC in development work:*** The current investments and policies supported by development agencies have impacts on emissions of BC and organic carbon. The agencies could consider describing the climate effects of these emissions alongside other project impacts, initially in qualitative terms. A key aspect for agencies is the cross-cutting nature of BC emissions, which can be affected by activities in a number of sectors. These include the energy, environment, transport, industry, rural, health, and urban sectors. Projects and policies in which the impact of BC and organic carbon could be considered include those involving diesel use in transport and power, coal use in industry and the residential sector, biomass use in the residential sector, and open burning of biomass. Where relevant, the impact on regional climate, through atmospheric brown clouds (ABCs) and snow and ice melting, could also be described.

- ***Support projects that reduce BC to yield climate and health co-benefits:*** Assessment would be needed of the combined costs and benefits of such projects. Several areas merit consideration for support. Policies and projects that promote a reduction in PM emissions from diesel (both in transport and power generation) should probably be strongly encouraged from a climate change perspective. The scientific evidence that lower emissions of PM from diesel reduce global warming is strong, as is evidence of the harm to health. Projects that substitute cleaner fuels (primarily natural gas, biogas, and liquefied petroleum gas) for industrial and residential coal in urban and rural areas should be encouraged from both climate and health perspectives. Policies concerning residential biomass emissions will continue to be driven mainly by considerations of public health as well as by other local environmental and social factors. However, evolving evidence of the impacts of PM from biomass on global climate should be closely monitored. Development agencies could introduce BC emissions into discussions with the private sector. Since BC is not included in the Kyoto Protocol, and hence is not linked to carbon markets or low-carbon financing, innovative financial and policy solutions may need to be explored if projects are to go beyond conventional development finance.
- ***Fill the knowledge gaps:*** Improved analysis can be done on the economic costs and the health and climate co-benefits of mitigating BC and other PM emissions. Agencies' knowledge base in project economics, pollution control, and climate mitigation strategies could give them an advantage in addressing the problem. Agencies could consider supporting efforts to improve knowledge of the magnitude, sources, and effects of BC emissions in developing countries. Data on emissions from biomass cooking should be a priority. Further research may be needed into policies and projects for introducing clean transport fuels and corresponding advanced vehicle technology in developing countries, including ULSD and compressed natural gas (CNG). Other measures to reduce PM from diesel could also receive more analytical attention from a climate change perspective, including modal shifts in transport, introduction of more effective vehicle inspection, retrofitting of high-emitting vehicles, and less reliance on diesel in power generation.
- ***Explore global and regional policy options to include BC in climate change policy:*** In the context of global climate policy, BC is considered along with other short-lived climate forcers, such as ozone. BC and non-Kyoto gases are primarily a global climate issue, not specific to developing countries. Nonetheless, development agencies can take a role in addressing the nature of BC emissions from developing countries, within the context of low-carbon development and green growth options. Development agencies could consider how to include BC in the formulation of climate change policies and strategies, taking into account the policies of the United Nations Framework Convention on Climate Change (UNFCCC). Agencies should keep abreast of the rapid progress of research and policy in this area. "Low carbon" growth strategies for countries could

consider, in a qualitative manner, the impact of BC and other aerosol emissions on global warming, and assess measures for reducing emissions of BC where possible. More focus could be given to policies concerning the regional impacts of BC. Development agencies could reach out to regional partner organizations, including those dealing with the Himalayas and the Arctic.

1 Introduction

Black carbon (BC) consists of particulate matter (PM) emitted from the combustion of biomass and fossil fuels. It is widespread in all regions, and is associated with certain activities in both developed and developing countries, including use of biomass and coal for cooking and heating, and diesel use in transport and power generation. Development agencies thus deal with activities that generate or reduce BC, either directly or indirectly. Since BC has significant environmental consequences, an understanding of these is important for the agencies' operations and policies.

Over the past decade, BC has come to be recognized as one of the principal causes of global warming. In part because BC loading varies so much by location, this understanding has developed much more slowly than for the roles of GHGs such as carbon dioxide (CO_2) and methane, which have been the main focus of research. Recent research suggests that BC may be the second or third largest global warming agent. There is also evidence that BC changes the climate in regions such as South and East Asia and is a principal cause of ice and snow melting in the Arctic. PM emissions, including BC, are extremely harmful to health when inhaled. Thus it is now clear that the environmental consequences of emissions of BC are both local (health and environment) and global (climate change). BC, which has long been a concern of national environmental health policy, now needs to be seen also as an element in global climate policy.

A considerable body of scientific research has been conducted to understand better the role of BC in warming the climate. This work is part of a broader effort to clarify the role of PM (or aerosols) in the climate system, which poses major scientific challenges. While the research effort is expanding rapidly, many questions remain. Although having important climatic influences, BC and other aerosols were not included in the Kyoto Protocol, in part because of the limited understanding of their influences on the climate. In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC) stated that the level of scientific understanding of the climatic impact of BC and other aerosols was between "medium-low" and "low"[1] (Forster and others 2007). It is possible that by the time of the next major report in 2014, the IPCC will conclude that the understanding of these questions has improved sufficiently to consider whether BC and aerosols can enter more directly into international climate discussions.

The widespread use of biomass for cooking in developing countries makes emissions of PM, including BC, one of the leading causes of premature death and disease, mainly through damage to the respiratory organs. PM emitted from automotive vehicles, primarily those using diesel, is also a key factor in damage to health from urban pollution in both developed and developing countries. This has prompted long-running programs to reduce such emissions—for example, by improving the quality of cooking stoves in developing countries, and reducing PM emissions from transport.

1. For CO_2, and the other long-lived greenhouse gases covered by the Kyoto Protocol, the level of understanding was "high."

A key consideration when examining the effects of BC on the climate is the impact of aerosols that are co-emitted with BC—mainly organic carbon. BC emissions alone unequivocally exert a warming influence on the climate; however, organic carbon emissions exert a cooling influence. Thus, taking action to reduce warming from BC may mean reducing emissions of cooling aerosols, making the net effect uncertain. Much needs to be done to improve understanding of the composition and quantity of PM emissions from the main sources, particularly from residential biomass use.

Many actions to reduce emissions of BC also involve reducing CO_2 emissions. However, not all actions to reduce CO_2 emissions also reduce BC emissions. One example is the replacement of vehicles using gasoline with more efficient diesel vehicles that emit less CO_2. The diesel vehicles emit more BC, because emissions of BC from diesel are generally higher than from gasoline. In assessing the costs and benefits of actions to reduce CO_2 emissions, the impact on BC and aerosol emissions also needs to be determined. In order to preserve a clear focus on BC and aerosols, this report does not deal with the joint effects of BC and greenhouse gases (GHGs).

Climate modeling shows that a large reduction in the global amounts of BC emissions, without changes in emissions of organic carbon, would lead to a sharp onetime decrease in the warming influence of human activities. A rapid reduction in BC emissions has thus been proposed as a way to partially offset the projected increase in temperatures in coming decades[2]. This would not solve the long-term problem of climate change, which is caused by the GHGs, but it could extend the limited time that is available to reduce emissions of GHGs aggressively, before global temperatures reach dangerous levels. Proposals to reduce BC emissions also often address the need to reduce emissions of several other short-lived gases (such as ozone) that are mostly not covered by the Kyoto Protocol.

This paper is designed to inform development agencies, in a brief, simplified, and non-technical manner, about the links between BC and climate change, and how these could relate to development policy. The paper describes: (a) what is known about the impact of BC and related aerosols on climate, (b) the sources and importance of BC emissions, (c) possible actions and policies to mitigate emissions, and (d) considerations for agencies in light of these issues.

2. In practice it would be necessary to avoid a large associated decrease in organic carbon emissions, which could be achieved only through addressing certain activities, such as diesel use.

MESSAGES FROM: Integrated Assessment of Black Carbon and Tropospheric Ozone (UNEP and WMO 2011)

A small number of emission reduction measures targeting black carbon and ozone precursors could immediately begin to protect climate, public health, water and food security, and ecosystems. Measures include the recovery of methane from coal, oil and gas extraction and transport, methane capture in waste management, use of clean-burning stoves for residential cooking, diesel particulate filters for vehicles and the banning of field burning of agricultural waste. Widespread implementation is achievable with existing technology but would require significant strategic investment and institutional arrangements.

Full implementation of the identified measures by 2030 would reduce future global warming by 0.5˚C (within a range of 0.2–0.7˚C). The rate of regional temperature increase would also be reduced.

Full implementation of the identified measures would have substantial benefits in the Arctic, the Himalayas, and other glaciated and snow-covered regions. This substantially decreases the risk of changes in weather patterns and amplification of global warming resulting from changes in the Arctic. Regional benefits of the black carbon measures, such as their effects on snow- and ice-covered regions or regional rainfall patterns, are largely independent of their impact on global mean warming.

Both near-term and long-term strategies are essential to protect climate. Implementing both reduction strategies is needed to improve the chances of keeping the Earth's global mean temperature increase to within the UNFCCC 2˚C target.

At national and sub-national scales many of the identified measures could be implemented under existing policies designed to address air quality and development concerns. Improved cooperation within and between regions would enhance widespread implementation and address transboundary issues. International policy and financing instruments to address the co-benefits of reducing emissions of short-lived climate forcers need development and strengthening.

There is confidence that immediate and multiple benefits will be realized upon implementation of the identified measures. The degree of confidence varies according to pollutant, impact, and region. For example, there is higher confidence in the effect of methane measures on global temperatures than in the effect of black carbon measures, especially where these relate to the burning of biomass. Given the scientific complexity of the issues, further research is required to optimize near-term strategies in different regions and to evaluate the cost-benefit ratio for individual measures.

MESSAGES FROM: Abatement Opportunities for Non-CO_2 Climate Forcers (Climate Works Foundation, European Climate Foundation 2011)

While there is still much uncertainty around the emissions and abatement opportunities for black carbon and methane, nitrous oxide, and fluorinated gases, enough is now known to inform action. These non-CO_2 climate forcers collectively cause at least one quarter of global warming and accelerate the rate of temperature change.

Emissions from the four non-CO_2 climate forcers can be reduced by over 20 percent by 2030 using available methods: fugitive emissions capture, efficient agricultural practices, combustion optimization, diesel particulate controls, and alternative cooling technologies.

Reducing non-CO_2 emissions is essential to limit global warming during this century, slow the rate of temperature increase, and reduce the risk of adverse climate feedbacks. On top of the positive climate effects, 80 percent of the measures also improve public health and half come at a net savings to society.

While a large share of the measures is relatively straightforward to implement, capturing the remainder will be challenging, as millions of people would need to take action, some of whom are the world's poorest.

In developed countries, the principal abatement opportunities lie in waste management, air conditioning and refrigeration, and diesel engines. Opportunity areas for developing countries are diesel engines, natural gas production, waste management, and traditional combustion technologies.

2 Black Carbon and Climate Change

Black carbon exerts a large effect on the climate, but it does so in a very different way from the greenhouse gases. This chapter explains the nature of BC, provides an overview of its complicated interaction with the climate, and describes some of the challenges being addressed by science in this important area.

Description of Black Carbon

Black carbon differs from the other key anthropogenic substances affecting the climate in that it consists of particulate matter, rather than being a gas such as carbon dioxide or methane. BC is emitted from the burning of biomass and fossil fuels that contain carbon and is a product of the incomplete combustion of these fuels.[3]

On average, BC particles have a residence time in the atmosphere of at most two weeks, before they are washed down or fall to the ground. This compares with the millennia that the elevated CO_2 concentration persists in the atmosphere and continues to exert a warming influence on the climate. This is a key difference between BC (and other aerosols) and the "long lived" Kyoto gases: these gases accumulate in the atmosphere from one year to the next, but BC does not, it is constantly being removed from the atmosphere and replenished. Another difference is that BC does not mix uniformly throughout the atmosphere, tending to be found in some regions more than others.

3. Emission of soot is a sign of inefficient use of fuels, since the carbon thus emitted could have provided energy when burned in the presence of oxygen.

BC is often referred to as soot, as seen in smoke, and is the principal component of black soot. BC consists of light-absorbing particles of pure carbon that appear black to the naked eye. In practice BC is usually released together with other particles that consist of compounds of carbon with other elements (hydrogen, nitrogen, oxygen, and so forth). This combination of carbon with other elements constitutes "organic carbon" PM.[4] Organic carbon particles usually reflect some sunlight back into space.[5] Smoke emitted from the burning of different substances will vary greatly in the proportion of BC to organic carbon (Jacobson 2010). Smoke with a low proportion of BC relative to organic carbon will appear lighter to the eye than smoke with a high content of BC, which can appear black when the BC proportion is very high. Once emitted, both BC and organic carbon particles undergo chemical changes that will affect how they interact with the atmosphere, and hence how they will affect the climate.

An important characteristic of PM, including BC, is the size of the particles. There is no single definition of BC in terms of particle size. The literature is based upon particle sizes of 2.5 micron[6] or smaller, known as PM2.5. Because they have the largest radiative influence, most work deals with particles of 1 micron (PM1) and smaller, with particles being as small as 0.1

4. There are thousands of organic carbon compounds emitted as PM, which is a challenge to assessing their impact on climate change.
5. It has recently been recognized that some organic carbon particles consist of "brown carbon" which can absorb heat radiation (Ramanathan 2010).
6. A micron is one millionth of a meter (one thousandths of a millimeter).

micron. These small particles tend to have the greatest effect on climate, in part because larger particles generally do not stay aloft in the atmosphere long enough to have a significant impact (Bond 2004). Most measurements of PM are taken because of concerns about local health consequences; these also concentrate on the smallest particles, which are more likely to penetrate deep into the lungs to cause damage.

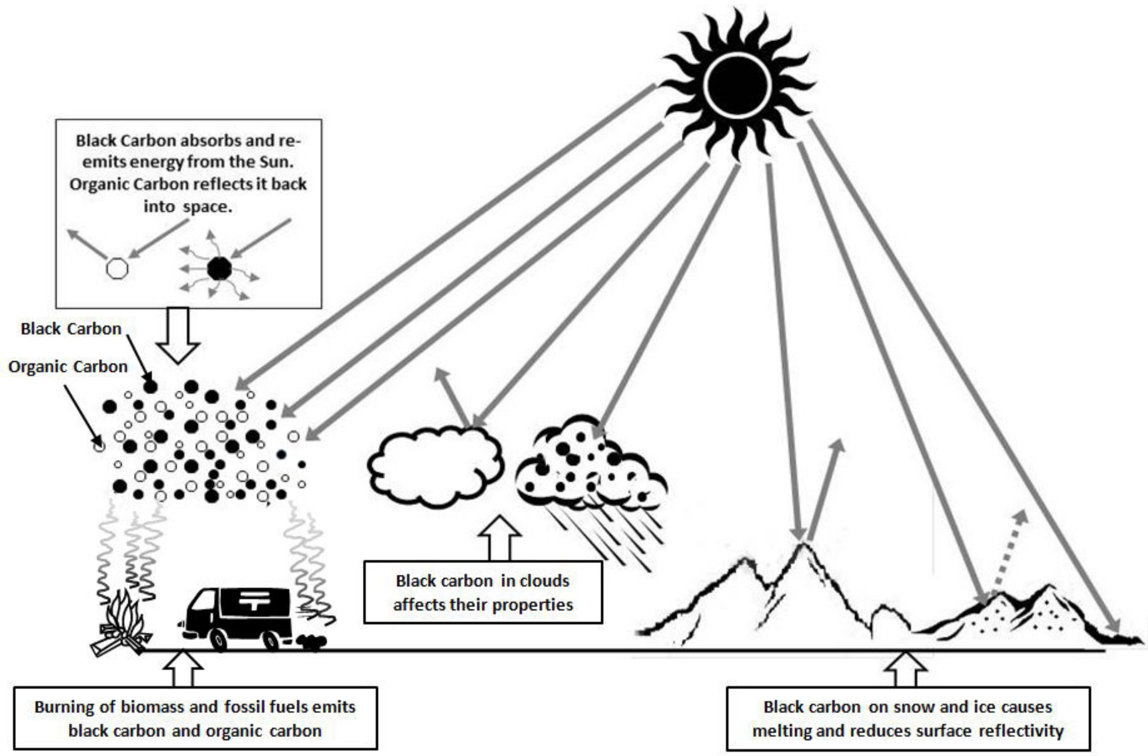
Effects of Black Carbon on Climate Change

The physical behavior of BC, and its mode of action in affecting climate, is fundamentally different from that of GHGs. BC affects climate in several ways (see Figure 1):

- BC absorbs solar radiation that it then gives off as heat, warming the surrounding air molecules. These warmed air molecules tend to travel farther than the BC particles, spreading the heat to the surrounding air.
- BC absorbs (then re-emits) solar infrared radiation that is radiated from the Earth's surface.
- BC deposited on snow and ice reduces the albedo (reflectivity) of the Earth's surface.
- BC interacts with clouds and with other PM to affect regional and global weather patterns.

GHGs interact with the atmosphere differently than BC particles and they do not tend to darken the Earth's surface. The gases warm the atmosphere by absorbing infrared light (that is, heat) radiation from the sun that is re-emitted upward mainly by the Earth's surface, and re-radiating half of the energy back toward the surface, adding to the normal warming by solar radiation.

FIGURE 1. The Impact of Black Carbon on the Global Climate



Source: World Bank 2011.

This heat-trapping effect is commonly known as the greenhouse effect.[7]

The impact of deposition of BC particles onto the surface is especially significant. When these particles land on snow or ice, they darken the surface, which causes more solar radiation to be absorbed and increases the rate of melting. This acceleration of melting both has a marked local effect and contributes to global warming, because the melting exposes darker surfaces (rock, soil, or water) and this leads to even greater absorption of solar energy (Hansen and Nazarenko 2004). This amplification of the natural albedo feedback is particularly effective in the Arctic because the seasonal snow cover and sea ice are relatively thin, so that accelerating the springtime melting leads to greater solar absorption all summer long (see Box 1). Most BC in the Arctic comes from surrounding regions of Europe and North America; however, some of it has been transported from South Asia and China (Quinn 2008). BC from the latter regions also affects the ice and snow of the nearby Himalayas. The reduction of snow and ice in the Arctic and Himalayas due to BC has been estimated to be as significant as that due to global warming (Ramanathan 2010). As is shown in Figure 2, the albedo effect of BC on snow and ice is significant, if relatively small, at the global level.

An important distinction between BC and GHGs is that the impact of the former on global warming

7. This is not a full or precise definition of the greenhouse effect. For a concise description see: Intergovernmental Panel on Climate Change Fourth Assessment Report, Working Group 1, Chapter 1: "What is the Greenhouse Effect?".

BOX 1. Effects of Black Carbon Emissions on the Arctic

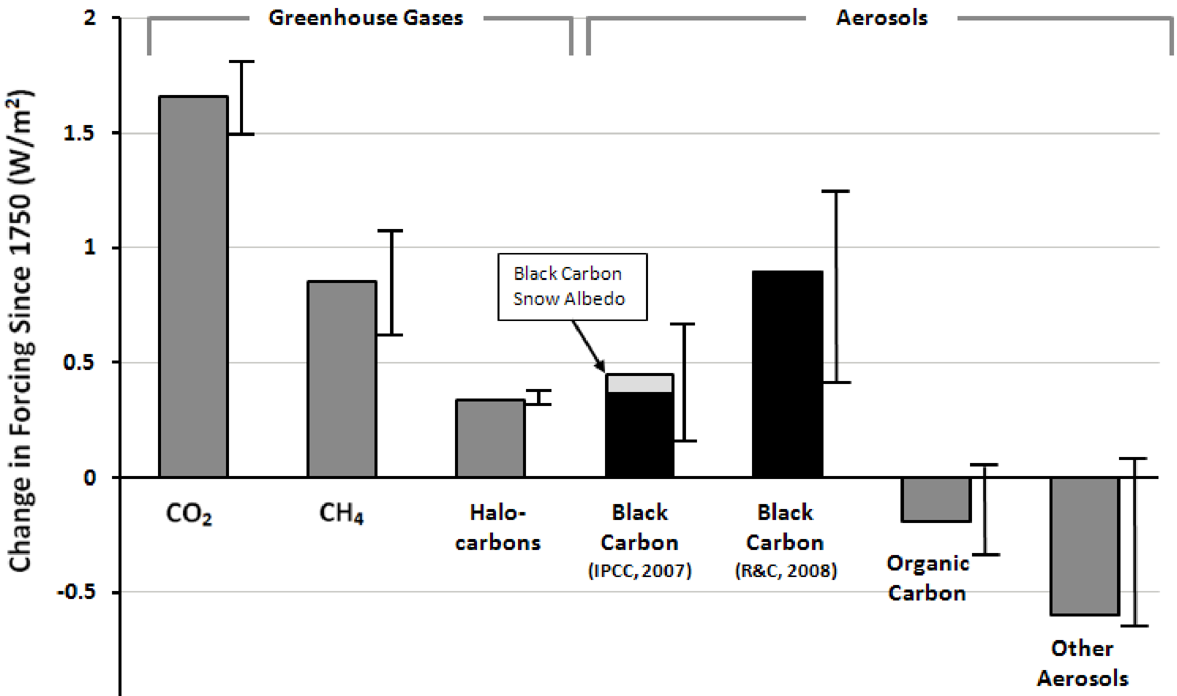
BC emissions have a disproportionate influence on the warming of the Arctic. Temperatures in the Arctic have risen twice as fast as the global average over the past 100 years, and BC may be a major contributor to this excess warming. This warming has been accompanied by earlier melting of sea ice in the spring, a longer melting season, and faster melting of the Greenland ice sheet. The total area covered by summer sea ice decreased by 40 percent between 1979 and 2007. The trend toward warming and melting has been attributed primarily to human-induced climate change (Pew 2009).

The impacts of ice loss include an important amplifying climate feedback—the reduction of the Earth's albedo (the ability to reflect sunlight back into space). BC landing on snow or ice absorbs heat and reduces its reflectivity, promoting melting. As warming causes greater amounts of snow to melt, bare land and dark ocean water are exposed, which absorb more solar radiation. This positive feedback leads to further warming and is one of the reasons that the Arctic is highly sensitive to BC. It has been estimated that a given amount of BC causes twice as much warming in the Arctic as it does in the rest of the world (Hansen and Nazarenko 2004). The changes in the Arctic climate have significant consequences for the land, ice, and aquatic ecosystems in the Arctic. Moreover, melting of Arctic land-based glaciers contributes to global sea-level rise.

Most of the BC received by the Arctic comes from activities in Northern Europe and North America; however, studies have shown that large quantities also come from regions below 40° N, particularly from South and East Asia. Pollution from these regions tends to be lofted to high altitudes and then carried for long distances. Further study will be needed to assess with precision the sources of Arctic BC (Quinn, 2008).

The melting of Arctic sea ice will effectively unlock the Arctic Ocean, leaving it increasingly open to human activity—particularly shipping and oil and gas production. The trends indicate an Arctic Ocean with longer seasons of less sea-ice cover of reduced thickness, implying that there will be improved accessibility to ships around the margins of the Arctic Basin. Until recently, seaborne transport of cargo in these waters has been very limited, and reported ship emissions have been low. Taking the Northern Sea Route via the Barents Sea between Europe and the North Pacific Region can reduce travel time by up to 50 percent, compared to the sea routes in use today. Increased shipping in Arctic waters will produce significant amounts of BC that will settle on Arctic snow and ice (IMO 2009).

FIGURE 2. Estimates of Radiative Forcing for Greenhouse Gases and Black Carbon



Source: World Bank (based on Pew Center on Global Climate Change. 2009).

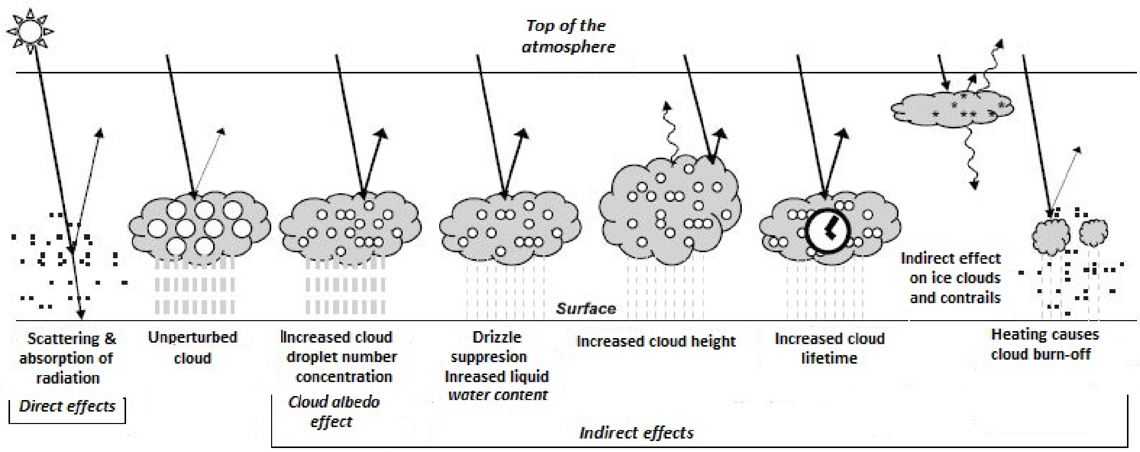
can vary significantly by region. In areas where BC concentrations are high, the warming effect of BC can be comparable to that of the main GHGs. BC contributes to the formation of atmospheric brown clouds (ABCs), which can have climate impacts over large regions. These ABCs are widespread loadings of PM in the atmosphere that cause visible dimming of sunlight; by changing the local climate energy balance, they affect precipitation patterns and temperature gradients. ABCs have been implicated in such regional weather alterations as shifts in the South Asian monsoon and changes in the rain distribution over eastern China (Ramanathan and Carmichael 2008).

The interaction of BC and organic carbon particles with water vapor causes changes in the nature and behavior of clouds. Given the importance of clouds in the dynamics of global warming, the effect of BC and other aerosols on climate via changes in clouds may be as important as their "direct" warming and cooling effects (see Box 2). These interactions are highly complex and not fully understood (Forster and others 2007). As the scientific understanding of the effects of the Kyoto Protocol gases on climate grows, the complications introduced by BC and aerosols have become an important factor in the remaining uncertainties in climate model projections (CCSP 2008). This is one of the reasons for the rapidly growing scientific interest in aerosols and BC among climate scientists in recent years.

Despite the additional scientific research over the past decade, uncertainty remains about the scale of the contribution of BC to climate change. There is no doubt that BC contributes to global warming, the debate is about the size of its contribution. This uncertainty is due primarily to limited information about BC's activity in the atmosphere and on the

BOX 2. Impact of Black Carbon on Clouds and Resulting Climate Change

Aerosols such as BC affect the climate both directly, by absorbing or reflecting light, and indirectly, through their interaction with clouds, snow, and ice. Aerosols can influence clouds in several ways. As the humidity of the atmosphere goes up (for example, by the air moving up, expanding and therefore cooling), the small particles take up water vapor to form small cloud droplets—with properties that are determined by the characteristics of the particles. The more the particles, the smaller the droplets and the more they reflect sunlight, thus cooling the atmosphere (the "cloud albedo effect"). Other indirect effects operate through changes in the intensity and type of precipitation, and by affecting the height and lifetime of clouds. These effects are significant, but are both complicated (involving feedback effects) and not yet well understood. Because of the variety and variability of clouds, the effects are difficult to observe and quantify. The RF of the cloud albedo effect has been estimated through global climate models that incorporate aerosols and other climate factors. Figures quoted by the IPCC range from -0.2 to -1.8 (that is, of the same order of magnitude as the direct RF of greenhouse gases and BC). Most of this variation is due to the different assumptions and mechanism of the models, and the need to simplify a very complex system. The effects of BC, through warming and possibly reducing planetary albedo (which can occur if the BC layer is above the cloud), are quite different from the influences of cooling aerosols. However, since all the aerosols exist in a mixed state, at varying concentrations by location and season, it is the combined effect that is important for climate.



Source: Forster and others 2007.

Earth's surface, questions about how BC interacts with other aerosols and clouds, and uncertainties about the global quantity and distribution of BC. The 2007 IPCC analysis estimated BC to be the third largest global warming agent, substantially behind CO_2 and methane (see Figure 2). However, a more recent widely cited analysis concluded that BC is the second largest contributor to global warming after CO_2 (Ramanathan and Carmichael 2008).

The measure used to estimate the impact of the effect of gases and aerosols on global temperatures is "radiative forcing" (RF). This is a measure of the change in the balance of incoming sunlight and outgoing infrared radiation caused by a gas or aerosol, relative to pre-industrial levels (A.D. 1750).[8] Amounts of RF for key gases and aerosols are shown in Figure 2.

As can be seen in Figure 2, global RF is dominated by CO_2 and methane (CH_4). The combined RF of these and the other Kyoto gases is +2.6 W/m^2. The impact of organic carbon and most other aerosols (except BC)[9] is negative and offsets some of the warming from gases.

8. It is measured in watts per square meter (W/m2) averaged over the globe.
9. Primarily sulfates, nitrates, and dust.

These substances reflect Sunlight back into space and thus cool the planet. The offset for organic carbon is about -0.2 W/m^2. BC occupies an unusual position in that it is both an aerosol and a major positive contributor to global warming. The IPCC estimate of RF for BC was +0.34 W/m^2 with a range of +/- 0.25 W/m^2. A further forcing of +0.10 W/m^2 is attributed to BC on ice and snow. Ramanathan and Carmichael (2008) suggest that the RF for BC is much greater, being as high as +0.9 W/m^2, which would make it the second largest cause of global warming after CO_2.[10] Attention should be paid to the error bars in the diagram which are proportionately much larger for aerosols than for long-lived GHGs such as CO_2 and methane, reflecting the lower level of scientific understanding of their effects on climate.

The "standard" measures of climate change impacts developed for long-lived greenhouse gases do not work well for BC and other aerosols. The main estimate of global warming impact is the "global warming potential" (GWP). This is an estimate of the total cumulative radiative forcing of one ton of a substance emitted today over a period of 100 years, or GWP100 (sometimes 20 years is used). GWPs are measured in relation to CO_2. With the CO_2 level calibrated as 1, the 100-year GWP of methane is 25, while halocarbons have GWPs of 1,000 or more. International climate policies generally refer to the GWP100.

Because the GWP100 is a measure of the ratio of the cumulative warming influence of a unit mass of a substance as compared to the warming influence of a unit mass of CO_2 over a century, it can be a poor metric for representing the effects of BC on climate. Except for the effects of BC on snow and ice, the warming effects of BC occur during the one or two weeks that the particles stay aloft in the atmosphere. This contrasts with the hundreds of years to millennia during which CO_2 continues to affect the climate. CO_2 accumulates in the atmosphere, with each year's emissions being added to those from previous years, while BC does not accumulate. The amount of BC in the atmosphere is approximately the amount emitted during one to two weeks (the time over which the BC in the atmosphere is "recycled"). In addition, the impact of BC is regional as well as global, which means that its effect on global warming (hence GWP) can vary according to where it is emitted (Forster and others 2007).

Despite its short atmospheric lifetime, the global warming effect of a quantity of BC is huge relative to an emission of the same mass of CO_2. Over roughly its two-week lifetime, one ton of BC can absorb over a million times more radiative energy than a ton of CO_2. The climatic importance of CO_2 arises from the fact that (a) global emissions of CO_2 are some 3,000 times higher than BC, and (b) the average atmospheric lifetime of CO_2 is thousands of times longer than BC (USAID 2010). At the global level the impact of BC on global warming is strong but short-lived and BC is scarce, whereas the impact of CO_2 is weak and prolonged and CO_2 is plentiful.

The large difference between the warming process of BC and that of CO_2 means that where an activity is adjusted to lower emissions of both CO_2 and BC (for example, reduction in coal burning), the latter will often have the greater impact on climate change over the next few years to decades.

The GWP for BC has been estimated at 680 over a 100-year period, and 2,200 for a 20- year period.[11] There are very large ranges of uncertainty around these mean estimates, reflecting the continued uncertainty about the atmospheric effects of BC (Bond and Sun 2005).[12] These estimates do not include the impact on ice and snow, which would raise the GWP of BC but also add to the uncertainty about BC's overall impact on climate.

10. With a range of +0.4 to +1.2 W/m2.

11. Since all of BC's impact is during the first one or two weeks, the amount of forcing is the same over a 100- or 20-year period. The impact of CO2 however, is considerably less over 20 years than over 100 years.

12. The ranges are 210 to 1,500 over 100 years, and 690 to 4,700 over 20 years.

3 Sources of Black Carbon and Their Impact on Climate Change

The main sources of BC are the burning of biomass and fossil fuels. Activities that generate BC emissions include: use of coal in the industrial and residential sectors, diesel and fuel oil use in engines, residential biomass use for cooking and heating, and open burning of biomass (see Table 1).

While all of the sources listed in Table 1 generate significant amounts of BC, there are large variations in the levels of emissions relative to raw material consumption and in the co-emissions of organic carbon. As stated earlier, the greater the proportion of BC emitted relative to organic carbon, the greater the net impact of an activity on global warming. This means that measurements of both BC and organic carbon are needed for each source, which makes estimation of emissions extremely challenging. Differences in emissions can be ascribed to generic

TABLE 1. Sources of Black Carbon and Their Impact on Climate

Fuel type	*Ratio: BC/ organic carbon*	*Climate impact*	*Emissions estimates*	*Key features*	*Mitigation policies*
Residential and industrial coal (PM not contained)	High	Net warming	– Volumes and trends known – Composition relatively uniform	– Mostly in China – Very harmful to health	– Substitution by cleaner fuels – Emission controls (industry)
Diesel	High	Net warming	– Volumes and trends known – Composition uniform	– Present in all countries – Growing fastest in developing countries – Harmful to health in urban areas	– Regulate vehicle emissions – Introduce ULSD and particle traps – Substitute cleaner fuels
Gas flaring	High	Net warming	– Volumes partly estimated	– Varies by flare efficiency and gas composition	– Effective flaring regulations – Market structure
Residential biomass use	Moderate	Uncertain	– Volumes and trends somewhat uncertain – Wide variation in composition	– Mostly in developing countries – May be harmful to health	– Introduction of improved cookstoves, cleaner fuels (for example, LPG)
Open Burning of biomass	Low	Net cooling	– Volumes and trends very uncertain – Wide variation in composition	– Both natural and anthropogenic	– Policies on crop burning and wildfires

sources (biomass, diesel, and so forth), but there are also major variations within sources, depending on the specific nature of the material input (for example, type of wood), the technology used for combustion (type of stove or boiler), and the way in which the technology is used. To this must be added the unfortunate fact that for many BC and organic carbon emission sources, there are limited data on the scale of activities on which to base aggregate estimates of emissions.[13]

Coal

Coal use in households and industries is a significant source of BC. Households use coal for both cooking and heating. Industries use coal as a basic energy source. While the main use of coal is in the power sector, large power stations are equipped with filters that remove nearly all direct emissions of PM. Coal use does increase other aerosols in the atmosphere, particularly through emission of sulfur dioxide (SO_2) that creates sulfates. Ash may also have an effect. These latter aerosols generally have a cooling effect.

Coal burning emits BC and very little organic carbon. Coal use in the residential sector is less widespread than biomass. It occurs almost exclusively in areas where local sources of low-cost coal are available and access to cleaner fuels is restricted by economic circumstances. The largest concentration of use is in China, which also has the largest uncontained emissions from coal in industry; however, in recent years the government has targeted emissions from both household and industrial coal use for reduction, with considerable success. In the industrial sector the worst problems with coal emissions are from smaller and poorly regulated plants in major sectors such as iron and steel and cement. These plants are uncompetitive with large modern facilities and sector restructuring is thus reducing BC emissions. Small industries, such as brick kilns, are more difficult to control and represent a major source of BC in some urban areas in Asia.

13. This section uses information from Bond and others (2004) and Bond and others (2007).

Diesel Fuel

Use of petroleum fuels is a very substantial source of BC emissions in many parts of the world. Most emissions come from the middle distillates and heavy oil products. Of these the largest is from diesel use in three categories: on-road vehicles (trucks, cars, buses, and so forth), off-road vehicles (agricultural and construction machinery), and stationary sources (power generators). The heavy forms of diesel and fuel oil are used in ships and larger power generation units. Diesel use emits few organic carbons and it is thus a major source of net warming from BC (see Box 4). However, there is a variation in the intensity of BC emissions from diesel between countries, depending upon whether they have implemented fuel and vehicle standards to contain emissions of PM. Emissions from use of gasoline in vehicles are usually much lower than from diesel, and those from the lightest petroleum products, butane and propane, are minimal.[14]

BC emissions from diesel vary considerably between individual vehicles and types of vehicles. Off-road vehicles and stationary engines generally have higher BC emissions than cars and trucks. Shipping is also a significant source of BC, accounting for about 3 percent of worldwide emissions. BC emissions from shipping have a larger warming effect when they occur at northern latitudes and impact the snow and ice cover of the Arctic (see Box 1). Hence emissions of BC from shipping, like emissions from most other sources, will have a strong regional component that then affects the global environment through induced changes in the local weather (Quinn and others 2008). Among cars and trucks a proportion of vehicles can be classified as "smoke-belchers" or "super-emitters" with BC output 5 to 10 times that of average vehicles (due to poor maintenance and other deficiencies). Such vehicles can make up 15 to 20 percent of all vehicles in developing countries, and thus account for a large proportion of total BC emissions.

14. Gasoline vehicles can emit more significant quantities of BC and other PM when very poorly maintained.

The Organisation for Economic Co-operation and Development (OECD) countries account for the majority of global diesel use, but demand has been growing most rapidly in developing countries. As with biomass, the PM emitted by diesel is extremely harmful to human health. This is a major environmental issue in cities where PM concentrations are high, as is the case in many large cities in developing countries. The direct and indirect impacts of diesel on health are the prime reasons why there has been a shift to cleaner diesel technology in high-income countries. The beneficial effects of this move on climate change, through a large reduction in BC, have until now been incidental to policy. Policy in developing countries also aims to reduce PM in cities, but as is explained below this has not yet led to large reductions in BC emissions. As with coal, the reduction in SO_2 emissions from diesel has led to a reduced cooling effect from sulfate aerosols.

Gas Flaring

A likely source of significant BC emissions is the flaring of natural gas from production and processing facilities. This practice, although increasingly controlled in many countries, persists in many regions, the most notable being the Niger Delta in Nigeria and West Siberia in Russia (GGFR 2011). While burning of pure methane emits almost no BC, "rich gas" contains much heavier hydrocarbons including natural gas liquids. When flared, rich gas can emit very large volumes of BC. In the case of flaring, an important consideration is the efficiency of the flare—how much of the total volume of gas and liquids is burned. Improving the efficiency of flaring may be one way to reduce BC emissions from flares until they are eliminated by the processing and use of the gas. The global volumes and characteristics of PM from flaring have not been estimated.

Residential Biomass

Biomass is the most widely used fuel for cooking in rural areas of developing countries; it is extensively used in the poorest parts of cities as well. A wide variety of fuels is used: wood (either gathered as "dead wood" or taken from living plants), charcoal (manufactured from wood, usually harvested from standing forests), agricultural wastes (including rice stalks, wheat, and maize), and animal waste (dried dung).

Given the large number of poor households exposed to PM from biomass cooking, the burning of biomass is a critical issue for development policy (Barnes and others 2011). Despite the importance of the health and climate change issues involved, there is surprisingly little concrete scientific data on emission factors for biomass use, such as the total PM emissions and the ratio of BC to organic carbon. Like open burning of biomass, use of wood for cooking in traditional stoves (which account for the vast majority) produces substantial amounts of organic carbon alongside BC. However, since the combustion of biomass in residential fuels is contained, and more efficient than in open burning, the ratio of organic carbon to BC is much lower (see Box 3).

The net influence on climate of PM emissions from residential biomass will depend in large part upon the ratio of BC to organic carbon. Research has shown that within reasonable ranges of this ratio, it is possible for emissions from residential biomass to have either a small net warming or a small net cooling effect on climate (see Box 3). It thus cannot be asserted with confidence that reducing emissions of PM from biomass cookstoves will, in all cases, reduce global warming. Some mitigation strategies, such as introducing cookstoves designed to reduce PM, could both reduce the emissions of PM and affect their composition. This adds to the uncertainties in this area (Ramanathan 2010).

This judgment takes account of both the "direct" effects of BC and organic carbon on climate (that is, through heating and cooling due to the particles in the atmosphere), and the "indirect" effects through the impacts on clouds and the deposition of BC

BOX 3. Impact of Particulate Matter Emissions from Residential Biomass on Climate

Residential biomass burning emits both BC and organic carbon; however, their proportion is such that neither has an overwhelmingly dominating effect when compared with emissions from open burning, diesel, and coal use. Rough estimates of the ratio of BC to organic carbon for residential biomass range around 0.2 to 0.3, compared with around 0.1 for open burning and 3.0 for diesel. In other words, if the fossil fuels stand at one end of the scale with a large predominance of BC, and open burning stands at the other end with a predominance of organic carbon, residential biofuels sit somewhere in the area between them.

The RF estimates for residential biomass emissions are derived from global climate models. Results from these depend upon a large number of variables in addition to the levels of BC and organic carbon emissions. Important parameters for the PM itself include the size ranges of particles, mixing state of the particles, and chemical evolution of BC particles after emission. These models estimate both the direct effect on climate of BC and organic carbon, and the indirect effects. The direct effects exclude influences through clouds (see Box 2), while the indirect effects measure the influence from interactions of aerosols with clouds. The total effect of PM on climate is the sum of the direct and indirect effects. The direct effect of biofuels use on climate is generally seen to be slightly warming, with the influence of BC being dominant over organic carbon. However, the indirect effect may be cooling. Since the RF of the indirect effect is of the opposite sign to the net direct effect and of the same order of magnitude, climate models cannot yet ascertain with a high degree of confidence whether the total effect of biofuels use on climate is cooling or warming.

Studies that have specifically used global climate models to assess the influence of residential biomass emissions on the climate have come to differing conclusions: (a) Unger (2008 and 2009) concluded that the RF from residential biomass use had a small positive sign, (b) Aunan (2009) concluded that the best estimate for the RF was zero (with very large uncertainty), (c) Jacobson (2010) concluded that household biomass had a warming impact on climate, (d) Bauer (2010) came to the conclusion that the net influence of biomass use was cooling, and (e) Koch (2011) came to the conclusion that the indirect effect may dominate the direct effect for biofuels, resulting in overall negative RF. All of these models concluded that the absolute level of the RF from residential biomass was probably small, whether positive or negative. This level was in all cases significantly smaller than the positive RF due to emissions from diesel and coal use. The different studies used different models and assumptions, and their varying results demonstrate the considerable uncertainties in this area and the need for continued research.

As in other areas relating to BC, the absence of widely applicable physical data on actual volumes and types of emissions remains a major constraint. Even the simple ratio of BC to organic carbon, which is key to results, is roughly assumed. A wide range of improved biomass cookstoves is available, but little is known about the impact of these on BC and organic carbon emissions. Since the ratio of BC to organic carbon is likely to vary between locations and types of biofuels, field measurements may find that biomass use in some localities would tend to have a warming influence on the global climate, while in others it could have a cooling influence.

From the perspective of policy, the scientific uncertainty about the net warming impact on climate of the use of biomass for fuel would counsel caution in making assumptions in this area. The impact of biomass use on health is so clear and pressing that it will continue to be the main justification for urgent action to replace traditional cooking stoves with cleaner stoves and clean fuels. However, it should be noted that while the impact of biomass use on global climate may be uncertain, it has definite impacts on regional climate and resources, through snow and glacier melting, and formation of atmospheric brown clouds.

on snow and ice. The indirect effects on clouds are generally considered to be cooling, and of similar orders of magnitude to the direct effects. The impact on snow and ice is warming, though relatively small in global terms, and will strengthen the warming effect of residential biomass burning. Additional factors to be taken into account include the size distribution of particles, their concentration at various heights in the atmosphere, and the evolution of their chemical properties after they are emitted (Bauer and others 2010). Research in this area requires use of large global climate models and is continuing with increasingly sophisticated models incorporating all of these factors. The impact of BC from biomass may vary regionally due to its contribution to ABCs (Ramanathan and others 2008).

There are formidable difficulties in obtaining data on BC and organic carbon emissions for the major part of biomass use. Emissions will vary greatly by location and time. Each village or group of urban users will have their characteristic fuel use patterns, and there may even be large variations within this group. In the case of charcoal, emissions of BC and organic carbon will occur both during manufacture and in final use. There is far less uniformity in the emission characteristics of residential biomass use than in any other area of energy use. An additional consideration is that current policy initiatives emphasize replacement of traditional stoves by a wide variety of improved stoves (Barnes and others 2010). The effect of these stoves on the relative emissions of BC and organic carbon is not well understood. When suitably designed such stoves greatly reduce indoor PM concentrations, with corresponding benefits for health. If BC is reduced much more than organic carbon, the resulting new composition of PM will be less warming than the original composition, and vice versa. Much more concrete data are needed about the overall composition of emissions from contained biomass burning in order to reach conclusions about its impact on climate.

In addition to PM and CO_2, biomass burning emits other gases that contribute to global warming, including methane, carbon monoxide, nitrogen oxide and other non-methane hydrocarbons. Accounting for these gases may increase the warming impact of emissions from biomass burning on the climate. However, improved stoves also have a different GHG emissions profile from traditional stoves. Policies that reduce PM emissions from biomass use will also tend to reduce the emission of such GHGs, and alter their relative composition.[15]

Open Burning of Biomass

A range of sources contributes to BC emissions from open burning of biomass. These include both naturally occurring wildfires and sources due to specific human activities. The latter category includes (a) regular burning of field crop residues after harvest, which is a common agricultural practice in many parts of the world, and (b) forest fires set deliberately in order to clear land for agricultural uses.

Open burning of biomass produces far more organic carbon than BC. Estimates of emissions from various types of burning put the mean ratio of BC to organic carbon at around 0.1, compared with about 3.0 for diesel transport. Within the central ratio there are very wide variations, but organic carbon will tend to dominate. This means that open burning has on balance a cooling effect in the atmosphere. However, the BC from open burning of biomass still affects snow and ice, hence smoke from open burning that reaches Arctic areas and snow and glaciers elsewhere could have a warming effect. This is the case with much of the open burning in Northern Europe and Northern Eurasia, which has a large impact on the Arctic (Box 1). Open burning also contributes substantially to the formation of regional ABCs.

15. Kerosene, one of the main substitutes for biomass in poor rural areas, may also emit BC if not burned cleanly.

It should be noted that open burning differs from other sources of BC in that a large proportion of the emissions are not anthropogenic—that is, they existed naturally before human intervention, as wildfires. This presents challenges in measuring the additional impact of human activities in the total.

Climate change and the rising CO_2 concentration can also affect the return period of natural wildfires. An increase in the CO_2 concentration, and the increase in water use efficiency that this causes, tends to increase the growth rate of plants. Thus a critical fire mass builds up faster. As summer heat becomes hotter and plants and soil become dryer, fire risk increases.

4 Global Volumes of Black Carbon Emissions

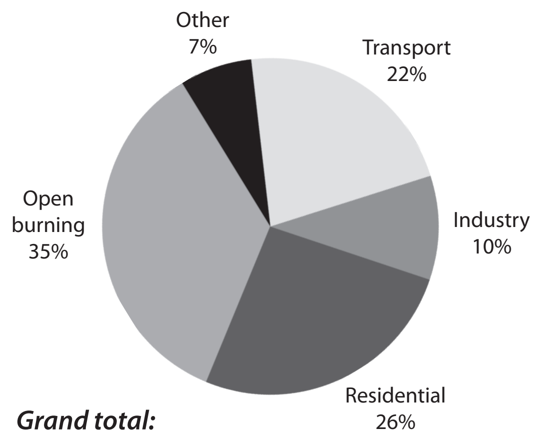
Only one estimate of global emissions of BC and organic carbon has been attempted using engineering parameters based upon bottom-up activity levels (Bond and others 2004). This estimate is derived from an extremely comprehensive and rigorous analysis of hundreds of different sources and technologies. While there can be confidence that the global estimates are of the right order of magnitude, the research suggests that the overall estimates are correct within a factor of two. Uncertainties about the volumes, sources, types, and regional distribution of PM necessarily limit the accuracy with which global climate models can incorporate BC and organic carbon into climate projections. Uncertainty also complicates identification and assessment of mitigation strategies to deal with the impact of BC on climate. More measurement and research are needed before global volumes of BC and organic carbon can be estimated with significant accuracy. However, remaining uncertainties should not detract from developing policies based upon the clear messages of climate science and of extensive analysis and surveys already completed.

Assessment of BC and organic carbon levels by satellite may be possible; however, there are technical challenges in distinguishing between BC and organic carbon, and in arriving at comprehensive global figures. Ground or air monitoring can also measure point concentrations of PM, but these are too few to provide reliable data over large regions, and also do not cover all altitudes at which PM may be present (CCSP 2008).

Estimates of total emissions of BC, derived from the sole current global estimate available, are shown in Figure 3. As can be seen, the largest contribution is from open burning (35 percent), followed by the residential and transport sectors. Figure 4 shows that the pattern of emission sources differs substantially between developed and developing countries, with the latter producing most emissions from the residential and industry sectors and the former from the transport sector.[16]

Global emissions of BC from energy use have grown significantly, but less so than total energy demand, due primarily to improved pollution controls. The estimated annual output from fossil fuels has risen from

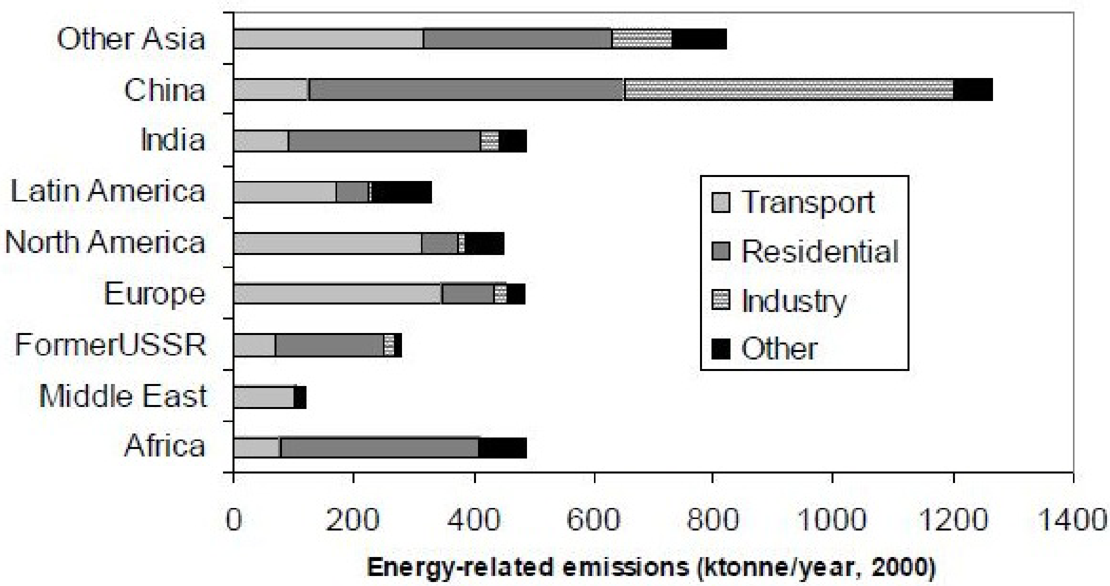
FIGURE 3. Global Sources of Black Carbon Emissions, 2000



Source: Bond 2010.

16. The estimated emissions from open burning are very difficult to attribute to regions at present.

FIGURE 4. Black Carbon Emissions from the Energy Sector by Region, 2000



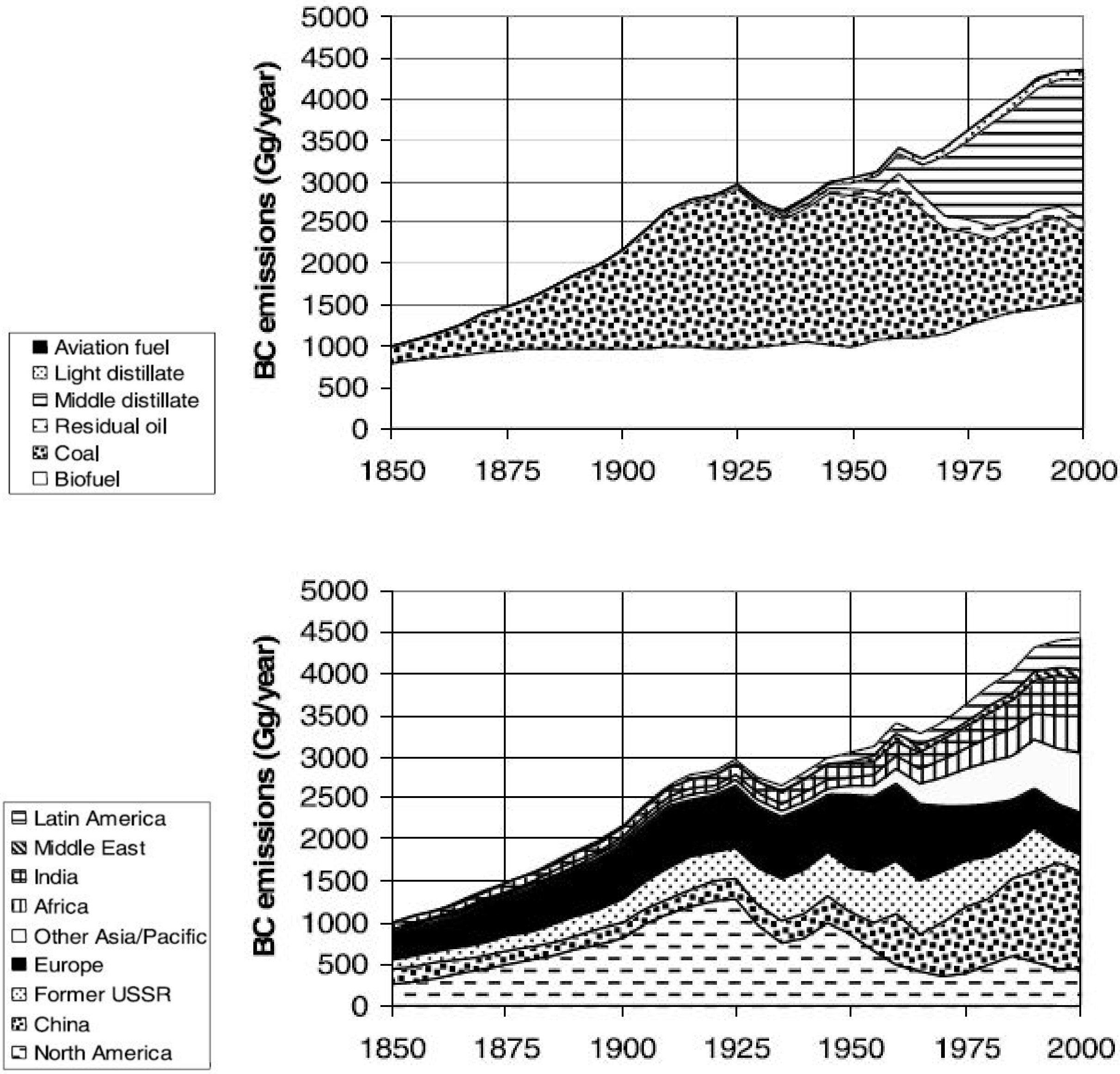
Source: Bond 2010.

1.0 million to 4.6 million tons/year between 1850 and 2000 (Bond and others 2007; see Figure 5). By comparison, total fossil fuel use has risen by a factor of ten over the same period. The 20th century saw a shift in BC sources away from coal toward petroleum, despite the rapid growth of coal use. This reflects the installation of emission controls (for all PM including BC) in power stations, while emissions from diesel (middle distillates) remained largely uncontrolled. BC output in OECD countries has fallen in recent decades due to greatly improved controls over coal emissions, and more recently from stricter standards for diesel combustion. Emissions in developing countries have continued to grow from all fuels.

Long-term trends in economic development and environmental controls are likely to lead to declining global BC emissions. Contrary to the case of CO_2, BC has tended to decline with economic development, particularly where a priority has been given to controlling vehicle emissions. Rising incomes in developing countries will bring a steady move away from residential biomass and coal use—as well as uncontrolled coal use in industry—toward cleaner fuels. Developed countries that have introduced ultra-low sulfur diesel, along with vehicle emissions standards, will see a fairly rapid decline in emissions from diesel as the vehicle fleet turns over. ULSD simplifies the use of particle traps in vehicles that remove BC from emissions (see Box 4). One area of rapid growth for BC in coming decades will be in emissions from diesel in developing countries where the introduction of ULSD, along with stringent emissions standards, is not yet a firm policy in most countries. However, these improvements will take place over coming decades as incomes rise.

While it may be thought that the problem of BC will eventually solve itself as global emissions from anthropogenic sources decline to relatively low levels—perhaps between 2050 and 2100—this should not lead to complacency in making emissions reductions, either from the point of view of health or from the point of view of controlling climate change. As discussed in Chapter 6, accelerating the reduction in BC emissions can be an option to limit global warming in the near term.

FIGURE 5. Historical Emissions of Black Carbon by Fuel and Region



Source: Bond and others 2007.

5 Black Carbon Mitigation Policies and Costs

Mitigation of BC in order to reduce global warming is new to the global policy agenda. To date nearly all policies that have reduced BC emissions have been motivated by factors other than global warming, usually control of local environmental and health impacts of PM. Options to further reduce BC emissions generally entail building on those initial control policies.

Practical technologies for eliminating BC from emissions are generally well known and are established as standard in many parts of the world. Difficulties arise with implementing appropriate policies, including paying the cost of updating and replacing equipment. A fundamental dilemma for controlling BC in the atmosphere is that approximately 60 percent of it is emitted together with large proportions of organic carbon in open burning and residential biomass (see Figure 3). The only options for reducing BC with minimal effects on other types of PM occur for coal and diesel fuel use. Hence, while much literature dwells on policies for reducing BC from all sources in order to limit global warming, in practice only reductions from coal and diesel use could achieve this objective with any degree of certainty.

Coal

Residential coal use is confined to a few countries, with the largest use being in China. Relatively successful interventions in China have done much to reduce the problem, but significant usage remains: some 400 million people still use coal for heating and cooking (IEA 2010). This usage and resulting BC emissions should be susceptible to further interventions.

Uncontrolled coal use in industry presents two aspects. One is the large-scale use in simple iron and steel furnaces, coke making, and similar substantial industrial facilities. These basic facilities are often uncompetitive in terms of costs, so their complete closure in the interests of economic efficiency has tended to reduce BC emissions (Bond and others 2004).

More difficult to address is the widespread use of coal in small- and medium-sized enterprises, such as brick kilns. These industries are not regulated and operate many plants in a large range of localities, including major urban areas. Options to cut PM emissions from such small-scale operations may involve either switching to a cleaner but more expensive fuel such as natural gas, or complete closure of the operation. Brick kilns are a large pollution problem, particularly in Asia. They consume not only coal but also other fuels with high BC emissions, such as used tires (USAID 2010).

Diesel

Control of BC from diesel is a relatively straightforward problem to address from a technical point of view, given experience with transition to cleaner fuels in high-income countries. It is also, in general, a relatively expensive option for reducing BC emissions. Eliminating BC emissions from diesel use requires installation of diesel particulate filters (DPFs),[17] but in general this can only be done effectively with ULSD. Removal of sulfur from diesel to this degree calls for specialized facilities in oil refineries. The motivation for introduction of ULSD and advanced vehicle specifications in high-income countries has been the need to control urban pollution, rather than considerations of climate change impacts. It should be noted that reduction of sulfur in fuels alone reduces sulfate PM formed from SO_2, but it does not result in lower BC emissions. Hence introduction and use of ULSD will not reduce BC emissions from legacy vehicles unless these are retrofitted with DPFs.

In the case of diesel it is not necessary to deal with the dispersed and differentiated supply-and-demand profile of biomass fuels. Supplies usually come from a few large sources (refineries or import terminals), while technical standards for oil products, and to a lesser extent for vehicles, exist in most countries. Once ULSD standards have been implemented, control of emissions depends upon the rate of introduction of new vehicles with DPFs, and the number of filters retrofitted to the legacy fleet. Because of the relatively slow turnover of the diesel vehicle fleet, the elimination of BC emissions from vehicles can take up to 25 years (Baum 2010).

While high-income countries have adopted ULSD standards, developing countries have been reducing the sulfur content of fuels more slowly and are generally some way from introducing ULSD (see Box 4). This would require significant additional investments in the refining system. In the absence of ULSD, the main strategies for reducing BC emissions from diesel in transport are the following:

- Fuel conversion by replacing diesel with LPG or CNG, although CNG requires considerable investment in vehicle conversion and in supply infrastructure
- Implementation of control policies and regulation to reduce emissions from high-emitting vehicles ("super-emitters"), which can present institutional challenges
- A modal shift in transport, in which total fuel use is reduced through provision of mass transit with low-emissions vehicles (for example, electric trains and trams) or with bus rapid transit systems (which may use CNG).

17. Diesel oxidation catalysts reduce PM emissions using chemical catalysts, but they are typically less effective.

Two other major sources of BC are off-road diesel (for example, power generation, construction vehicles) and shipping. Off-road diesel emissions may be of the same order of magnitude as on-road emissions, but are harder to control (Bond and others 2004). Use of ULSD with particulate filters can largely eliminate BC emissions from heavy construction and agricultural equipment, although regulation in this area lags behind that for road vehicles. Control of smaller stationary sources, such as power generators, is challenging because they are dispersed and hard to monitor (for example, residential generators); given the widespread use of small generators in developing countries, this is a considerable problem. Large diesel generators use lower-quality fuels and may present technical challenges for BC control. Shipping similarly presents technical challenges in eliminating BC and other PM.

Biomass

The key policy issues for biomass use concern the elimination, or substantial reduction, of PM emissions as a whole, not only of BC. The largest reduction in PM emissions occurs with a switch to fossil fuels such as kerosene and LPG. However, these fuels are at present not affordable to the major part of households in low-income countries. A reduction in PM emissions can also be achieved with suitable improved cookstoves, and by moving from direct use of biomass to efficient use of charcoal (Bailis and others 2005). Despite increasing penetration of more modern fuels, such as LPG and kerosene, the population of low-income countries continues to rely primarily on biomass for

BOX 4. Control of Black Carbon from Diesel Fuels

Most high-income countries have already mandated sale of ULSD and phased out higher sulfur grades of diesel. New vehicles are fitted with diesel particulate filters, and as a result virtually all PM emissions from diesel engines are expected to be eliminated as the fleet turns over. In the United States, almost complete elimination of BC from diesel trucks is expected by 2025 (Baum 2010). In certain cases, such as large trucks that meet required specifications, retrofitting of DPFs may be justified, possibly with public subsidies, given the large health and climate benefits.

Developing countries also have been reducing the sulfur content of diesel, primarily as a way of reducing SO_2 and related pollutants, but as yet with little impact on emissions of BC. While some countries still tolerate very high levels of sulfur (1,500 ppm or more), many countries have come down to 350 ppm or even 50 ppm. However, 50 ppm is still too high for full use of DPFs. Few developing countries are as yet planning to introduce ULSD (10–15 ppm). Costs for reducing sulfur tend to increase sharply in the transition from 50 ppm to 10 ppm, due to the high cost and difficulty of adapting refineries to produce ULSD. A study for the Asian Development Bank estimated the cost of introducing ULSD in Asia to be between 1.1 and 1.4 U.S. cents per liter of diesel. About half of this cost is to take standards to 50 ppm, and the rest from 50 ppm to 15 ppm (ADB 2008). The cost is equivalent to about 10 to 20 percent of total refining margins; therefore, while introduction of ULSD may increase retail fuel prices by only 1 to 2 percent, the absolute investments required are still large. In addition, older refineries may need to be closed. Countries struggling to build refining capacity to keep pace with oil product demand may be reluctant to increase the cost of refining in the short term by mandating ULSD.

A problem for developing countries is control of emissions from specific vehicles. High-income countries tend to have strict codes that limit emissions from vehicles and may mandate regular testing, which greatly reduce the number of diesel super-emitters. In developing countries it is hard to enforce codes that prevent super-emitters from operating. Establishing an effective inspection and maintenance program for road vehicles to deal with super-emitters and other poorly maintained vehicles is a challenging task for countries with limited institutional and technical capacity. Problems include inadequately trained personnel, poor test equipment, lack of oversight and enforcement, and fraud and corruption. The problems can be addressed with careful design of an inspection and maintenance program and provision of adequate resources. The program can be made self-financing through inspection fees and the work can be contracted out to private operators (USAID 2010).

Shipping accounts for about 1 to 2 percent of global BC emissions (Bond 2004). Ships have been subject to almost no restrictions on fuel use. Most of their consumption is in international waters and they therefore may lie beyond the reach of national regulations. The diesel engines on ships (low-speed diesels) use heavy grades of diesel and fuel oil. Such engines emit high volumes of BC as well as SO_2. International standards for ship fuel use are in the process of being introduced. Regulations will require use of ultra-low sulfur fuels, which will reduce the large amounts of SO_2 emissions from ships and thus volumes of cooling sulfate PM. The use of ultra-low sulfur fuels will not, however, reduce emissions of BC, and DPFs are not generally suitable for large marine engines (Schneider 2010). The net effect will be warming as fewer sulfate particles offset the warming from BC. BC emissions from shipping are a particular concern given the large amount of marine traffic in waters close to the Arctic. Pressures are growing in international forums to consider how to address the problem of marine transport BC emissions (IMO 2009). The example of fuel standards for ships illustrates the importance of taking account of the impact of PM on climate when making decisions about fuel quality and use.

cooking and water heating. A total of 2.5 billion people live in households using biomass fuels in unimproved stoves (Barnes and others 2011).

Reducing emissions of PM, including BC, from cooking in poor households has proved challenging. Problems have included the following:

- Difficulty of designing new low-cost durable cookstoves that meet the needs of consumers while reducing PM substantially
- Affordability of new stoves to poor households
- Problems maintaining condition and use of clean stoves after distribution
- Inertia among households long accustomed to indoor smoke

- Limitations on distribution systems for new clean fuels
- Affordability and availability of new fuels, particularly for LPG
- Cultural factors favoring cooking styles using open fires

These problems are substantial, but they can be overcome with well-designed policies, supplemented by appropriate funding where needed. Most governments, however, have not placed reduction of biomass use and associated emissions high on their list of energy sector priorities. This may be changing with an increased focus on health indicators, such as in the Millennium Development Goals, and rising income levels in many countries, such as India (Wilkinson and others 2009). Another factor may be growing activity among private suppliers of clean stoves.

In spite of the overwhelming evidence of health benefits, international support for the reduction of PM from biomass use by households is generally felt to have been inadequate. To date, multilateral development banks and bilateral donors have not provided large resources for this purpose. Interventions have been small and isolated. It has proved difficult to design and implement large-scale projects for cookstove conversion. Some governments have also given low priority to obtaining international assistance in this area. Rural energy policies have focused more on electrification than on provision of clean fuel for cooking and heating (Barnes and others 2011).

While the health benefits of reducing exposure to PM from residential biomass use are well known, the impacts of such reduced PM emissions on the global climate remain uncertain. Hence policies for the reduction of residential biomass use will most probably continue to be based primarily on health grounds, rather than on the need to reduce global warming. However, the regional climatic impacts of BC emissions could factor into mitigation policies. The deposition of BC on snow in areas such as the Himalayas tends to accelerate melting of ice and snow, disrupting regional water supplies. Further effects occur from ABCs that disrupt regional weather and precipitation patterns and consequently affect agriculture. As continuing research clarifies the impacts of PM emissions from biomass use on climate change, these impacts could be considered more definitely as an aspect of policies on biomass use.

Costs of Mitigation

The cost-effectiveness of BC mitigation with respect to climate change impacts has just begun to be investigated. The few estimates available are subject to a large number of uncertainties in terms of cost data, technical parameters, and assumed impact on global warming. Much more work is needed in this area. By contrast, extensive work has been done on the costs and benefits of options to mitigate GHG emissions.

In looking at the total costs and the climatic benefits of reducing BC, several factors need to be taken into account:

- The direct impacts on global warming of lower BC emissions
- The offsetting impact on warming of reduced associated emissions of organic carbon
- The indirect impact of BC and other aerosols on clouds
- Changes in net emissions of CO_2 and other GHGs
- Health co-benefits of reductions in BC and associated aerosols

Two studies[18] that have attempted to assemble estimates of mitigation costs looked at the relative costs and benefits of reducing BC through specific actions in several sectors. In order to compare the costs of reducing warming through reducing BC with the cost of doing so through GHGs, a conversion for the warming impact from BC units to CO_2 equivalent

18. USAID 2010, Kandlikar and others 2009.

units is needed. This has been done using GWPs, although this method has shortcomings (as noted above). In looking at BC mitigation, these studies have only taken into account the estimated global warming impact of BC, and have not considered the offsetting direct cooling effect of organic carbon, or indirect effects. Because of this, such studies could be misleading concerning the costs and benefits of actions related to residential biomass use. The calculations done for diesel and coal may be approximately correct, because BC dominates emissions. Preliminary conclusions include the following:

- ***Replacing residential coal stoves with LPG stoves (in China):*** In terms of global warming, most of the benefits from such a switch come from reducing the BC emitted by the coal. Substitution of coal by LPG reduces, but does not eliminate, CO_2 emissions. The cost of such substitution (an LPG stove and cylinder, cost of LPG fuel) is high for poor consumers. Costs for such an intervention can be as low as \$10/ton CO_2 equivalent. This intervention also has considerable health benefits.
- ***Switching of heavy-duty diesel vehicles (consuming high-sulfur diesel) to CNG:*** This option is very effective in reducing BC, but capital costs are relatively high for vehicle conversion and new infrastructure. The impact of this change on health will be greatest in urban areas.
- ***Retrofit of existing heavy-duty diesel vehicles with particle traps:*** Such retrofits are relatively expensive and reduce fuel efficiency. They are usually only an option when ULSD is available and vehicles meet certain minimum technical specifications. While BC emissions would be reduced substantially, the overall cost could be high when compared to the economic benefits for both climate and health.
- ***Repair super-emitting diesel vehicles:*** Since such vehicles typically make up about 15 to 20 percent of the fleet in developing countries, and may emit up to 10 times as much BC as the average vehicle, the repair of half of these high-emission vehicles could cut total BC emissions from the fleet by about one third. This is a highly cost-effective means of reducing BC emissions and their impact on climate. The net value of the health impact may also compare favorably with indoor pollution reduction.

Additional BC reduction options that have been looked at include: (a) retrofitting DPF to light-duty vehicles, (b) an effective inspection and maintenance program to ensure improved performance of all vehicles, and (c) changing to a new kiln type in low-tech coal-fired brick kilns. Of these, (b) and (c) may be the most attractive in terms of the cost of emissions reduction.

Much more work needs to be done in this area, as the estimates available are limited, are based upon sparse data, use uncertain climate impacts for BC, and do not take account of the direct and indirect impacts of all PM. The effect of reducing BC emissions on climate needs to be combined more systematically with the benefits for health. Furthermore, measures to reduce BC will involve changes in GHG emissions. A consistent basis is needed to combine the costs and benefits of the climate and health impacts of reducing BC emissions with those from changes in GHG emissions.[19] Actions to reduce BC emissions thus generate a range of potential costs and benefits for climate and health, including: (a) lower global warming from reduced BC emissions, (b) impacts on climate from PM emissions associated with BC (such as organic carbon), (c) impacts on climate from changes in GHG emissions, and (d) effects on health of lower emissions of BC and other PM. The challenge in evaluating mitigation policies for BC is to assess all these costs and benefits, and then to combine them in a consistent manner.

19. See Bailis and others for an example of how reduction in PM can be integrated with large positive health outcomes and changed GHG emissions from policies on biomass use. Such work could be supplemented by assessment of the net impacts on climate of emissions of BC and organic carbon, as estimates of such impacts improve.

6 Black Carbon and Global Climate Change Policy

The possible role of BC in international climate discussions has usually been examined along with short-lived gases that were not included in the Kyoto Protocol, such as ozone.[20] Methane is also regarded as one of such "short-lived climate forcers" (SLCF), although it was included in the Protocol. The positive RF of ozone and methane is estimated by the IPCC to be of the same order of magnitude as BC. The global warming effect of all the SLCF is high, making them attractive targets for mitigation. Some have advocated a focus on eliminating BC and other SLCF rapidly, as a way of delaying the temperature increase that is already built into the levels of CO_2 in the atmosphere. This would not be a substitute for urgent action to reduce GHG levels, which are the drivers of global warming in the long term.

The impact of eliminating BC from the atmosphere would be a onetime change in temperature levels. The short residence time of BC means that this change would take place within months. There is effectively no cumulative impact in the atmosphere from past emissions[21]. In the case of CO_2, climate change today results from the cumulative emissions from the past century or more. A reduction in CO_2 emissions will not bring about an immediate lowering of temperatures.

It has been suggested that the onetime reduction in global temperatures resulting from elimination of BC and the short-lived gases could "buy time" for the world to act decisively to limit concentrations of GHGs to levels consistent with manageable increases in temperatures. The overall cost of mitigation could be reduced, as future CO_2 reduction technologies will probably be more efficient than today's. Delaying the onset of higher temperatures also lessens the risk of catastrophic (runaway) global warming. It has been estimated that the reduction in global warming from eliminating all BC emissions would be equivalent to the continuing impact of 10 to 20 years of CO_2 emissions (for a target of 450 ppm by 2100) (Bice 2009). The world could live with a somewhat higher level of atmospheric CO_2 before hitting key trigger points in terms of unmanageable increases in global temperatures, such as a rise in excess of 2°C.

One suggested approach would be to widen global climate agreements to include BC and short-lived GHGs (MacCracken 2009). This approach would require high-income countries to pursue aggressive policies to reduce emissions of CO_2 and other GHGs. Developing countries would, in a first phase lasting several decades, focus on reducing short-lived warming agents (partcularly BC), on improving their carbon intensity, and on reversing deforestation. The intention would be that all countries should be brought into a global framework for reducing global warming agents. Under this framework, it is suggested that avoiding hard CO_2 targets for developing countries over the next few decades would permit them to pursue economic development that will almost inevitably entail some increases in CO_2 emissions. This would address the point that dealing with the needs of developing

20. Ozone is formed in the atmosphere by ozone precursor gases, including carbon monoxide, nitrogen oxides, and methane.
21. The feedback effects from BC deposited on snow and ice will be cumulative. In addition, the warming of the oceans due to the climate effect of BC emissions will take many years to dissipate.

countries for latitude in CO_2 emissions has been one of the main difficulties in formulating a global climate agreement.

This approach proposes changing the basis of climate discussions by focusing on the fact that reducing BC and short-lived gases is justified by the co-benefits for health arising from eliminating (a) BC from cooking smoke and diesel and (b) urban smog from gases such as ozone. This reduction is a part of the economic development process that could be accelerated to yield substantial positive climate impacts as a co-benefit.

From a practical point of view, this approach needs to consider that elimination of BC from the atmosphere would necessarily also involve a large reduction in organic carbon concentrations as biomass emissions of PM are cut[22]. Hence, if the concern is about limiting short term warming, reducing emissions of BC from biomass would not be the highest priority. The principal activities to be addressed in reducing emissions of SLCF would be road transport as the major emitter of BC, and large emitters of methane such as fermentation of organic matter, production of oil, gas and coal, and rice cultivation (Jackson 2009). In policy terms, comprehensive implementation of an architecture for BC reduction on a global scale would seem very challenging given the well-known difficulties in agreeing a global climate treaty. Moreover, attempts to introduce BC into climate discussions have proved politically controversial. Developing countries often see a focus on BC as an attempt to divert attention from developed countries' contributions to CO_2 emissions, which account for the bulk of global warming. Since much BC is emitted from cooking by the rural poor, these discussions can inadvertently, and inaccurately, portray the poor as causing global warming. Unfortunately, policy discussions have often ignored the uncertain net warming impact of residential biomass emissions, focusing on BC only, rather than on the combined effects of BC and organic carbon.

22. The assessment of the approach has usually been made with climate models that vary one atmospheric species at a time, such as removing BC without varying organic carbon. Models can vary more than one species (see Box 3), but the complexity of modeling and interpretation increases considerably.

To avoid the potential adversarial effects of introducing BC into global climate discussions, it has been suggested that a focus on regional agreements may be more productive (Wallack 2009). This also takes into account the strong regional effects of BC emissions, as seen in the Himalayas and the Arctic. In such cases the impacts on countries may be more specific and evident—such as changes in regional water supplies and weather patterns—than those from generalized global warming. These direct impacts could create a short-term national incentive to participate that is more difficult to achieve when dealing with CO_2. Precedents for such regional frameworks exist, for example in the UN Convention on Long-range Trans-boundary Air Pollution, which brings together countries in the European space (Bice 2009).[23] This Convention is considering whether BC can be incorporated into its provisions (UN ECE 2010).

Prospects for introducing BC into global climate policies are also affected by continuing uncertainties about the magnitude and mechanics of BC's influence on climate change (Bond 2007). This is an important question, and it is one reason why substantial efforts are being devoted to research into the climatic impacts of aerosols, including BC. The conclusions of this work are expected to feature in the next IPCC report, due in 2014. While the scientific case for reducing BC to combat global warming is very strong, global policy formulation requires more precise data. For example, if BC were to be introduced into carbon trading schemes, a sound and widely accepted CO_2 equivalent value would have to be established. Moreover, actual policies to cut BC emissions would require a more precise understanding of how much of BC's warming effect is offset by the cooling effect from organic carbon emissions.

23. The Convention has helped coordinate action on reducing emissions of sulfur dioxide.

7 Considerations for Development Agencies

Black carbon has not been considered as an agent of climate change by multilateral and bilateral development agencies in the assessment of projects and policies. Consideration has focused on the local health aspects of PM, which include BC. The growing evidence of the role of BC in climate change suggests that agencies' focus on PM arising from health considerations could be supplemented by taking into account the effects on climate change. Project evaluations could include describing their effects on BC and organic carbon emissions, and the corresponding impacts on climate. Consideration could be given to promoting some projects that reduce BC substantially, taking into account both health and climate co-benefits. Agencies could also make a contribution to expanding knowledge about BC and climate change, including improving the understanding of how to evaluate the economic costs and benefits of BC reduction. Finally, agencies could consider how the evolving knowledge about BC and climate change may affect policies in relation to climate change, at the regional and global levels.

Mainstreaming Consideration of Black Carbon in Development Work

The current investments and policies supported by development agencies have impacts on emissions of BC and organic carbon. The agencies could consider describing the climate effects of these emissions alongside other project impacts. A key aspect for agencies is the cross-cutting nature of BC emissions, which can be affected by activities in a number of sectors. Awareness of the impacts of BC and organic carbon on climate thus needs to be present in many areas. Diesel use is affected by policies in the energy, environment, transport, health, and urban sectors. Energy, environment, industrial, and urban policies all affect use of coal by small industries and households. Use of biomass for energy and for cooking cuts across the energy, rural policy, forestry, health, and environment sectors.

As part of identifying the impact of project investments on climate change, agencies could consider including a description of potential climate impacts from BC and organic carbon resulting from projects. The description would most likely be in qualitative terms, given uncertainties over measurement and net climate impacts. Examples of projects where significant changes in BC and organic carbon take place include the following:

- ***Projects that have a significant impact on the level of diesel use in transport:*** A reduction in urban emissions of diesel PM may be brought about by public transport schemes, for example through bus rapid transit projects. They should reduce BC emissions by cutting overall vehicle miles and using high-efficiency diesel engines. Such projects have been implemented in Egypt, Nigeria, Colombia, and Peru. Some projects that encourage the use of heavy vehicles or shipping will increase BC emissions.
- ***Projects that involve power generation from diesel:*** Some projects may increase diesel use from generators to meet urgent power needs, while others

will reduce diesel use where diesel generation is replaced with cleaner alternatives (for example, from renewable power or natural gas) and private diesel generation is curtailed as power supply reliability improves.

- ***Reduction in industrial PM emissions:*** This would include reducing polluting emissions from brick kilns in urban areas (particularly in South Asia and China).
- ***Substitution of rural residential coal use with cleaner alternatives:*** Alternatives to coal include LPG and biogas.
- ***Reduction of local pollution through substitution of residential gas for coal in urban areas:*** This has been a feature of investments in urban gas distribution in such countries as China and Turkey, where seasonal heating loads are significant.
- ***Interventions that affect biomass use in rural and urban areas:*** Projects such as the introduction of advanced cookstoves, and substitution of LPG for biomass in cooking, have significant effects on both BC and organic carbon emissions.
- ***Projects with a large impact on open burning of agricultural wastes and forests:*** Some forestry and agricultural projects may lead to reduced open burning, with substantial reductions in organic carbon and BC emissions.

When interventions lead to large reductions in emissions of PM from the burning of biomass, the regional climate change impacts could be noted: (a) the lower BC emissions may reduce Arctic and regional melting of snow and ice, with consequent impacts on the regional environment and on water supplies, and (b) lower BC emissions may limit formation of ABCs with significant regional climate effects.

The agencies could consider greater coordination of activities relating to the health and climate-related impacts of BC and other PM. Coordination could be established among the relevant sectors, including environment, energy, agriculture, transport, and urban. There may be justification for a joint review of the climate and health impacts of BC and other PM as a coordinated exercise among these sectors. Some agencies could build on a comparative advantage for tackling BC, arising from an ability to cover all the relevant sectors and issues in an integrated manner.

Supporting Projects that Reduce Black Carbon to Yield Climate and Health Co-benefits

Agencies could consider supporting projects that reduce BC emissions to yield climate and health co-benefits. Assessment would be needed of the combined costs and benefits of such projects (see below). Several areas merit strong consideration for support. Since BC is not included in the Kyoto Protocol, and thus is not linked to carbon markets or low-carbon financing, innovative financial and policy solutions may need to be explored if projects are to go beyond conventional development finance.

Policies and projects that encourage a reduction in PM emissions from diesel probably should be strongly encouraged from a climate change perspective. The scientific evidence that lower emissions of PM from diesel reduce global warming is sufficiently strong to be used as a guide to policy. Certain policies to cut BC emissions from diesel could result in relatively low-cost reductions in global warming. The reduction in PM from diesel also has significant health benefits, especially in high-density urban areas. Policies of interest include the following:

- Vehicle inspection regimes that can force the repair of the highest emitting vehicles
- Replacement of diesel with CNG in vehicles, where gas is readily available and the infrastructure cost can be kept low
- Where the opportunity arises, analyzing and supporting introduction of ULSD in developing countries

- Targeting reduced use of diesel generators, particularly in urban areas.

Projects that substitute cleaner fuels (primarily natural gas and LPG) for coal in urban and rural areas should be encouraged. To date these projects have been justified on the basis of health and energy policies, and to this can be added a consideration of the likely mitigation of global warming from lower BC emissions.

Policies and projects concerning residential biomass emissions will continue to be driven mainly by public health considerations, as well as by other local environmental and social factors. While projects are considered and implemented on health grounds, it is important to the extent possible to take into account their potential impact on the global climate. To this end it would be essential to monitor evolving research and initiatives to improve the understanding of the effect of biomass emissions on climate change.

The development agencies that are suitably positioned could introduce BC emissions into discussions with the private sector, which has paid limited attention to BC in developing countries. Most of the areas outlined above include substantial private sector investment activity. While climate finance is not yet available for projects specifically to reduce BC emissions, government policies that take BC emissions into account could encourage private investment in this area.

Filling the Knowledge Gaps

Further research is underway to clarify the impacts on climate of emissions of BC and organic carbon. In parallel, improved analysis can be done on the economic costs and benefits from climate change of mitigating BC and other PM emissions in developing countries. The work would need to be closely integrated with the analysis of the effects of PM on health in urban and rural contexts. Agencies' knowledge base in project economics, pollution control, and climate mitigation strategies could give them an advantage in addressing the problem. Better estimates of co-benefits would help in decision making on policies and investments.

Agencies could consider supporting efforts to improve knowledge of the magnitude, sources, and effects of BC emissions in developing countries. Due to the technical nature of much of this work, some agencies may consider using their development expertise and global networks to partner with specialist institutions. Improving information about emissions from biomass cooking would be a particularly strong priority, as may be seen from the foregoing discussion. A further area in which BC emissions data is currently lacking is gas flaring; agencies engaged in this area[24] could use their specialized knowledge to estimate the contribution of flaring to BC and other aerosol emissions.

Further research into policies and projects for the introduction of clean transport fuels and corresponding advanced vehicle technology in developing countries may be called for. This could focus on progress toward introduction of ULSD and corresponding vehicle technologies for cutting PM emissions. Other measures to reduce PM from diesel can also receive more analytical attention from the climate change perspective, including modal shifts in transport, introduction of more effective vehicle inspection, and repairing of high-emitting vehicles to reduce PM emissions. Further research may also be needed on the climate benefits of the use of CNG as a replacement for diesel in transport. A considerable body of knowledge on the introduction of cleaner fuels, primarily with health considerations in mind, already exists. A climate dimension could increase the priority of additional work in this area.

24. For example, the World Bank and its partners in the Global Gas Flaring Reduction Partnership (GGFR).

Exploring Global and Regional Policy Options to Include Black Carbon in Climate Change Policy

In the context of global climate policy, BC is usually considered along with other short-lived climate forcers, such as ozone. Like the Kyoto greenhouse gases, BC and non-Kyoto gases are a global issue, not specific to developing countries. Nonetheless, development agencies can take a role in addressing the specific nature of BC emissions from developing countries within the context of low-carbon development and green growth options. Development agencies could consider how to include BC in their formulation of climate change policies and strategies. In this they would usually be guided largely by progress in dealing with BC at the UNFCCC. Agencies should keep abreast of the rapid progress of research and policy in this area.

Low-carbon growth strategies for countries could consider the impact of BC and other PM emissions on global warming and assess measures for reducing emissions of BC where possible (for example, through introduction of ULSD and cutting the use of small diesel generators). This would need to be done initially at the qualitative level, given uncertainties of measurement and climate impacts. Including BC in the outlook for the energy sector would help to provide a more comprehensive view of how growth policies will impact climate. An example that can arise in this context is the perception of diesel as a transport fuel with less climate impact than gasoline, in terms of CO_2 emissions alone. This view may be altered if the unconstrained emissions of BC, which are higher for diesel than for gasoline, are also taken into account.

More focus could be given to the regional impacts of BC. This is particularly the case for the ABCs in India and China, the snow and glacier melt in the Himalayas, and the effect of BC on the Arctic. Development agencies could reach out to regional partner organizations, including those dealing with the Himalayas and the Arctic. The likely impact of BC emissions from developing countries on the Arctic means that there may be a role for the agencies to help Arctic nations address their concerns.

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