A policy-relevant summary of black carbon climate science and appropriate emission control strategies

June 2009

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

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The following individuals attended the 2009 International Workshop on Black Carbon held 5-6 January in London, UK. This document was informed by discussions held there and by subsequent follow-up with workshop participants.*

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* All presentations and materials distributed at the UK workshop are available online at http//www.theicct.org. Workshop attendance does not necessarily imply endorsement of this document. The ICCT takes sole responsibility for its contents.

EXECUTIVE SUMMARY

This document provides policy-relevant guidance on black carbon. The information it contains is consistent with the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 2007 and is further informed by the 2009 London International Workshop on Black Carbon [1] and subsequent discussions with workshop participants.

Black carbon is a solid particle emitted during incomplete combustion. All particle emissions from a combustion source are broadly referred to as particulate matter (PM) and usually delineated by sizes less than 10 micrometers (PM10) or less than 2.5 micrometers (PM2.5). Black carbon is the solid fraction of PM2.5 that strongly absorbs light and converts that energy to heat. When emitted into the atmosphere and deposited on ice or snow, black carbon causes global temperature change, melting of snow and ice, and changes in precipitation patterns.

Fossil fuel combustion in transport; solid biofuel combustion in residential heating and cooking; and open biomass burning from forest fires and controlled agricultural fires are the source of about 85 percent of global black carbon emissions. Maximum feasible reductions in 2030 can capture 2.8 Tg/yr of black carbon, a reduction of 60% from business as usual. Co-emitted pollutants and the location of emission activity will determine the net impact of control strategies on the climate.

Public health protection is already a strong argument for actions that control black carbon. Exposure to PM is responsible for hundreds of thousands of global deaths each year. Actions that reduce PM such as new requirements for exhaust after treatment with lower sulfur fuels, fuel switching and reductions in fuel consumption can reduce a substantial fraction of black carbon emissions. Regardless of the climate protection benefits, there is a strong case for these actions to protect public health.

The climate impacts of black carbon reinforce the public health need for actions to control PM emissions. According to the IPCC, black carbon is the third largest contributor to the positive radiative forcing that causes climate change[2]. One kilogram is about 460 times more potent than an equivalent amount of carbon dioxide over a 100-year time horizon and 1600 times more potent over a 20-year horizon based on unofficial IPCC estimates[3]. IPCC estimates of radiative forcing are conservative compared to others in the published literature.

Controls on black carbon can produce rapid regional and global climate benefits. Like all aerosol particles, black carbon washes out of the atmosphere within a few thousand kilometers from its source, so it produces essentially short-lived radiative forcing. This forcing produces strong regional climate impacts that extend beyond the forcing region and approach a global scale. In the aggregate these regional impacts are a global problem. A climate change mitigation strategy that incorporates short-lived forcing agents like black carbon can more rapidly reduce the positive radiative forcing that causes climate change, especially when rapid action is needed to avert tipping points for large-scale impacts like the loss of Arctic summer sea ice, the Himalayan-Tibetan glaciers, and the Greenland ice sheet.

Black carbon reductions supplement but do not replace actions to control carbon dioxide and other greenhouse gases. A focus of climate change mitigation is to reduce all positive radiative forcing, and carbon dioxide is the largest positive forcing agent, so any delay in CO2 emission reductions extends its climate impacts. Actions that reduce black carbon and carbon dioxide emissions in parallel will more effectively reduce total positive radiative forcing.

Controls on black carbon will reduce both positive and negative radiative forcing, so decisions to act on a climate basis alone should focus on the net effect. Black carbon is emitted with other pollutants that reflect light and offset its positive forcing. These include primary and secondary organic carbon, sulfates, and nitrates produced in amounts that vary with the combustion and fuel type of each source. The net effect of sources is modified by the transport and deposition of its black carbon emissions onto ice and snow, so major sources that produce negative forcing in the atmosphere can still be net positive forcers if they deposit sufficient amounts into the Arctic or atop mountain glaciers.

The highest priority targets strictly from a climate mitigation perspective are sources that cause net positive radiative forcing such as combustion of fossil fuels low in sulfur and deposition of black carbon on ice and snow surfaces. On-road heavy-duty diesel vehicles, off-road agricultural and construction equipment, residential coal combustion, and industrial brick kilns are generally net positive forcers. Open agricultural burning, residential biofuel burning and commercial shipping may be negative forcers, but this can be offset locally if there is black carbon deposition on snow and ice.

SCIENTIFIC ASSESSMENT

Human activities are causing changes in the Earth's climate. Among the most important of these changes is an increase in average global temperatures induced by absorption of long-wave infrared radiation by greenhouse gases and strongly light-absorbing aerosols. Atmospheric scientists call this change a positive radiative forcing. Reflection of energy is a negative forcing associated with cooling. The IPCC estimates that human activities since 1750 are associated with a total net positive radiative forcing of 1.6 Wm^{-2} [0.6 to 2.4], which is associated with a 0.8°C [± 0.2] increase in average global temperature since the late 1800s.

Black carbon refers to any number of strongly light-absorbing combustion particles, the strongest of which is soot[4]. The particles vary in size but generally they are much smaller than PM2.5 and may not even get as large as PM0.1. Black carbon is always a component of particular matter emitted from combustion sources, but the amount emitted will vary by the type of fuel used, the combustion process, and the performance of any emission control technologies or practices.

Black carbon lasts about one week in the atmosphere, but this can vary by up to a factor of three depending on the combustion process and the location of the emission[5]. Carbon dioxide, on the other hand, produces perturbations that are long lived such that most CO2 emitted today will impact future climate for 30 to 100 years, and some produce impacts for even longer.

Black carbon is an important contributor to the positive radiative forcing that causes climate change. The largest share of this forcing comes from the direct absorption of light energy in the atmosphere. The IPCC estimates that through this effect black carbon is responsible for about 0.34 Wm^{-2} [± 0.25] in globally averaged radiative forcing[6]. Research cited in the IPCC report shows that this warming effect can be magnified when black carbon particles are incorporated within (or mixed with) other particles that scatter light energy such as sulfates[7], but most climate models used by the IPCC did not take this amplification into account. Thus this estimate is probably too low.

Some impacts of this direct radiative forcing include not only increases in temperature, but also changes in precipitation and surface visibility. Plumes of emissions can suppress convection and stabilize the atmosphere in ways that obstruct normal precipitation patterns. They dim the Earth's surface, reducing patterns of evaporation that feed the formation of clouds.

Black carbon also produces positive radiative forcing by changing the reflectivity or albedo of bright surfaces like snow and ice. Under pristine conditions these surfaces reflect a high fraction of solar energy back into space, but black carbon particles above or on these surfaces absorb a substantial fraction of this energy and re-emit it as heat. This not only reduces the amount of solar energy reflected, but it can also evaporate clouds and melt snow and ice. This decline in snow and ice surface area produces a feedback loop that can induce additional warming and melting. The IPCC estimates the global albedo effect of black carbon on snow to be 0.1 Wm^{-2} [±0.1].

Given the direct radiative forcing and snow albedo effects estimated by the IPCC, the total radiative forcing of black carbon is estimated to be 0.44 Wm^{-2} [± 0.35] This ranks black carbon as the third most important positive climate-forcing agent after carbon dioxide and methane.

The IPCC appears to provide conservative guidance on black carbon. For example, the definition it adopted is broad and the radiative forcing estimate is at the low end of the possible range. This is due to a situation where the climate science of black carbon is developing rapidly, but the pace of the scientific community in filtering, debating and consolidating this new knowledge is moving slowly.

The IPCC did not quantify the contribution of black carbon to the cooling effect of clouds, which could reduce the estimate of its total radiative forcing. Most models also failed to take into account internal mixing, which could increase the estimate. Greater understanding of internal mixing and contribution to cloud burden will likely be reflected in the next IPCC report due in 2013.

STRATEGIC VALUE

Black carbon reductions will provide substantial public health benefits and stand on their own as a strong reason to reduce emissions. It is clear that black carbon is a fraction of particulate matter emissions that are associated with premature death, disability, and chronic disease. Black carbon may fall into the category of ultrafine particles or PM0.1, which pose a significant health risk. These small particles are emitted primarily from combustion sources. The World Health Organization estimates that in the year 2000 urban air pollution was responsible for 800,000 premature deaths and indoor smoke from solid fuels for 1.6 million premature deaths. Most of these occurred in developing countries.

Targeting black carbon will also achieve more rapid climate benefits than a strategy focused on carbon dioxide alone. Black carbon is one of a small number of climate-forcing agents with short lifetimes, so controls on sustained emissions will produce a relatively rapid decline in atmospheric concentrations. Climate abatement strategies can take advantage of this to quickly reduce the radiative forcing that causes climate change. This strategy can assist in the effort to slow the pace of global climate change and to reduce already committed global warming. But it can also be useful to delay and perhaps avoid some of the greatest regional tipping points such as the loss of Arctic summer sea ice and loss of the Himalayan-Tibetan glaciers. Their loss is developing rapidly, but given strong localized forcing from black carbon, emission controls can have a significant impact.

The policy community should be careful not to trade action on black carbon for action on carbon dioxide. Both produce positive radiative forcing that causes climate change and action on both is necessary to reduce this to achieve climate goals. Actions that reduce the most positive radiative forcing are the most desired, so policies that can simultaneously reduce both black carbon and carbon dioxide can be more effective than simply targeting each one individually.

Black carbon reductions may be required to offset declines in emissions of other short-lived forcing agents One example is the ongoing control of sulfur dioxide emissions. These emissions are declining rapidly around the world as fuel controls are imposed, and there is no question that these actions are necessary to eliminate adverse public health impacts. Since sulfates are strongly light-reflecting, these controls reduce negative radiative forcing, which is equivalent to a positive radiative forcing. And since sulphate precursors are short-lived, this positive forcing occurs relatively rapidly. But black carbon reductions can reduce positive radiative forcing on an equally rapid time frame. Even more, many of the controls necessary to reduce black carbon, such as those used in transportation, are enabled by the same policies to reduce sulfur emissions.

GLOBAL WARMING POTENTIAL

For policy makers convinced by the science and the strategic importance of black carbon controls, a common next step is the application of the global warming potential (GWP) to the full inventory of emissions, an evaluation of the full CO2-equivalent reduction potential of the multi-pollutant "basket" of emissions, and analysis of the most cost-effective control strategies. Black carbon introduces complexity into this process and requires answers first to some fundamental questions: What is the overarching policy goal? Is it necessary to include black carbon in a multi-pollutant basket? If so, how should the metric be designed to compare greenhouse emissions? This guidance is necessary to navigate among the choices inherent in the application of weighting factors.

The GWP is a weighting factor designed to communicate the ratio of the integrated radiative forcing of a greenhouse emission to that of carbon dioxide. Integrated radiative forcing is simply the sum of the radiative forcing that a greenhouse emission produces over a chosen time horizon. For example, the IPCC in its fourth assessment report determined that the GWP for methane on a 100-year time scale is 25. That is, a pulse emission[8] of methane will produce over its lifetime twenty-five times the radiative forcing of the same quantity of carbon dioxide within a 100-year period.

The IPCC provides 20-year, 100-year and 500-year GWP values for every major greenhouse gas. In every application of the GWP this choice of time horizon is necessary. With black carbon this choice can appear difficult since the time horizon produces large variation in GWP values. This variation is explained by the differences between the time-dependent impacts of short and long-lived forcing agents. With black carbon, for example, a short time horizon like 20 years will capture all of its radiative forcing, but only a fraction of the forcing of carbon dioxide, a longer-lived agent. A longer time horizon like 100 years will still capture all of the forcing of black carbon, but it will also capture a greater fraction of carbon dioxide forcing, so the differences between their total forcing grows smaller over longer time horizons. This explains why the 100-year GWP for black carbon is much lower than the 20-year GWP.

But the selection of time scale should depend not on the greenhouse emissions being evaluated. It should depend on the overarching policy goal. If the goal is to avert global impacts to occur within 100 years, then the 100-year GWP (GWP100) is the appropriate metric. Global impacts expected within 20-years require the 20-year GWP (GWP20). The parties to the Kyoto Protocol chose to use primarily the 100-year time frame in calculating their emission inventories, which shows a preference for long term impacts and therefore, long-lived greenhouse gases. The choice of the shorter 20-year time scale would have indicated a concern for short-term climate impacts and placed greater emphasis on the role of black carbon and other short-lived forcing agents.

Black carbon is a very potent climate-forcing agent indicated by its GWP. Although the IPCC has never explicitly provided a GWP for black carbon, the information provided in the Fourth Assessment Report did provide a graphic representation of this GWP in Figure 2.22 located on page 206 of Forster et al (2007). In addition, information provided in Table 2.5 on page 164 of the same report provides the information necessary to estimate this value. The formula for the GWP is provided on page 210 is the following,

$$GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_i \cdot [C_i(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt}$$

where GWP_i is the time-integrated global mean radiative forcing of a pulse emission of 1 kilogram of compound *i* relative to that of the reference gas CO2. *TH* is the time horizon, a_i is the radiative efficiency of component *i*, and $[C_i(t)]$ is the time-dependent abundance of *i*. The numerator and the denominator are each referred to as the absolute global warming potential (AGWP). The AGWP values of CO2 for 20-years, 100-years and 500-years are found on page 211 of the report.

Since the average lifetime of black carbon is less than 1 year, the annual average radiative forcing is equal to the integrated radiative forcing for any time horizon (20, 100, or 500 years). And if the annual emissions are known for any average RF estimate, then the ratio of the two provides the integrated RF per Kg of emissions, which is equivalent to the AGWP. This method was applied to each AEROCOM study presented in Table 2.5 to produce a separate GWP, then each of these GWPs were averaged. Results are shown in Table 1. This approach is conservative since it provides only the GWP for the direct effect of black carbon and does not include the semi-direct, indirect or snow albedo effects.

Table 1. Global Warming Potentials (GWP) drawn from the IPCC 4th Assessment Report

	GWP20	GWP100	GWP500
Black carbon	**1600**	**460**	**140**
Methane	72	25	7.6
Nitrous oxide	289	298	153
Sulfur oxides	-140	-40	-12
Organic carbon	-240	-69	-21
Carbon dioxide	1	1	1

Note: The methodology used for black carbon was also used for organic carbon and sulfur oxides. Values for black carbon, organic carbon and sulfur oxides were not published by the IPCC and are not official estimates.

Application of the GWP assumes that the emissions being compared produce radiative forcing that is evenly spread across the globe, so any two emissions produce equivalent radiative forcing regardless of their location. But since black carbon is short-lived and its radiative forcing is regionally concentrated, this assumption does not hold. Short-lived aerosols travel short distances, producing strong regional radiative forcing sometimes referred to as "hot spots". The location and duration of this forcing will vary with local conditions that influence their lifetime and transport. Therefore, no two emissions of black carbon weighted by GWP can be expected to produce an equivalent radiative forcing. This suggests that black carbon emissions weighted by the GWP do not necessarily represent a CO2-equivalent value.

The IPCC acknowledged the limitations of the GWP in its application to short-lived forcing agents and called for a new metric for short-lived emissions in its 2007 report. It said "*To assess the possible climate impacts of short-lived species and compare those with impacts of the LLGHGs [long-lived greenhouse gases], a metric is needed.*"[9]. In 2009 it re-affirmed the GWP as the standard metric but opened the way for alternative approaches in its Fifth Assessment Report due in 2013[10].

Despite this, regional radiative forcing of black carbon produces climate impacts that are both regional and global in scale. Radiative forcing causes warming that extends beyond the forcing region. In the aggregate, the multiple forcing regions are a global problem.

An alternative metric to the GWP is the Global Temperature Change Potential (GTP). It is the ratio of temperature change from a pulse emission of a climate species to a pulse emission of carbon dioxide. Long-lived and short-lived pollutants that are equivalent in terms of GTP-weighted emissions will produce an equivalent global mean temperature response for a chosen year. This is to say that the GTP will produce a more accurate representation of the CO2-equivalent impacts of black carbon than will the GWP. However, policy makers will still need to choose a time period over which the metric will be calculated[11].

While the IPCC mentions the GTP in its most recent report, it does not provide values. A recent paper in press co-authored by leading scientists who drafted pieces of the IPCC report provides the estimates in Table 2.

The GTP uses an impact parameter that is further down the cause-effect chain and closer to the impacts on society; however, additional uncertainties are introduced: it varies with estimates of climate sensitivity and climate response time. As these estimates improve, the GTP for specific emissions will need to be recalculated. Like the

Table 2. Global Temperature Change Potentials (GTP) for black carbon and other pollutants

	GTP20	GTP100
Black carbon	**470**	**64**
Methane	57	4
Nitrous oxide	303	265
Organic carbon	-71	-10
Sulfur oxides	-41	-5.7
Carbon dioxide	1	1

Source: Fuglestvedt, J., K. Shine, T. Berntsen, et al. (2009) Transport impacts on Atmosphere and Climate: Metrics. *Atmos Environ* In press.

GWP it will vary with estimates of background conditions, and it does not quantify precipitation or snow melt impacts that may be important when analyzing black carbon aerosols. Nonetheless the GTP is a likely alternative to the GWP.

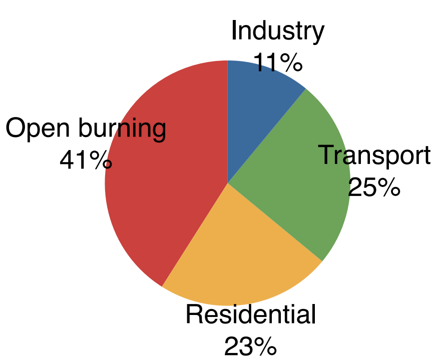
Without a common yardstick to compare short- and long-lived climate forcers, one option could be to exclude black carbon from multi-pollutant analyses, and establish separate objectives for its mitigation.

SOURCES AND TARGETS

The most recent inventory data show that the major sources of black carbon are fossil fuel combustion in industry, power generation, transportation and residential activities. Also significant is residential biofuel burning, agricultural fires, and forest fires.

Since black carbon is always emitted with a collection of aerosols, including some that are light-reflecting, it is necessary when identifying the highest priority targets to evaluate not only the inventory of emissions, but also the net absorption or reflection of those emissions and the magnitude of this effect. Organic carbon and sulphates are light-reflecting, so emissions that produce the lowest ratio of these components in relation to black carbon will cause the most positive forcing. This analysis should also take into account estimates of transport and deposition of black carbon onto ice and snow. Emissions that place the most black carbon onto these surfaces will produce the largest positive forcing at the surface. The exact threshold from negative to positive forcing for major sources is a subject of ongoing research.

Figure 1. Share of global black carbon emissions from all sources in 2000



Source: Bond, T.. (2009) Black carbon: Emission sources and prioritization. Presentation at the 2009 International Workshop on Black Carbon. 5-6 Jan 2009. London, UK.

Based on what we know about the composition of emissions from the major sources of black carbon, combustion of fossil fuels low in sulfur cause net positive radiative forcing, while residential biofuel burning, combustion of fossil fuels high in sulfur, and open burning can cause net negative forcing; however, when these sources are in close proximity to ice and snow, they can cause local positive forcing, the magnitude of which is unknown, but which may offset in whole or in part any negative forcing. Table 3 describes the priority source targets for black carbon based on this approach and Table 4 provides estimated maximum feasible reductions by major source category.

Table 3. "No-regret" targets to mitigate the climate impacts of black carbon

I. Diesel combustion in ...

- A. on- road heavy-duty vehicles
- B. off-road agricultural, construction and other vehicles

II. Near-Arctic emissions of ...

- C. biomass burning from forest fires and controlled agricultural fires
- D. diesel combustion in commercial shipping

III. Near-glacier emissions of ...

- E. biofuel burning in residential heating and cooking

IV. Low-sulfur coal combustion in ...

- F. residential heating and cooking
- G. industrial brick kilns

Table 4. Maximum feasible reductions from baseline emissions in 2030 (Gg/yr)

	Black carbon	Organic carbon	Sulfur oxides
Industry	621	502	457
Open burning	373	1,177	166
Transportation	1,032	397	1,950
Residential	750	2,404	2,043
Total	2,776	4,480	4,616

Source: Adapted from estimates by the International Institute for Applied Systems Analysis (IIASA); Michael Walsh, International Consultant; and Corbett & Winebrake, Energy and Environmental Research Associates (EERA).

Note: Estimates of carbon-equivalent emissions require a weighting factor like the GWP or GTP. For example, the CO2-equivalent black carbon emissions for industry in 2030 using the 20-year GWP are 621*1600=993,600 MMTCO2-eq(GWP20).

MITIGATION STRATEGIES

On-road transportation

Stringent emissions controls in highly motorized industrialized countries like the United States and the European Union are producing a global decline in transportation-related black carbon emissions, however, the global vehicle fleet is set to triple by 2050.[12] If no action is taken, then these emissions are predicted to rise again and reach levels 20 percent above year 2000 levels by 2050. High-polluting heavy-duty diesel vehicles are expected to remain the primary transportation-related source of BC emissions over this time, but motorcycles, light-duty gasoline vehicles and light-duty diesel vehicles should also be targeted.

The primary, most effective emission reduction strategy is installation of the wall-flow filter (also called the diesel particulate filter) on diesel vehicles. This can practically eliminate black carbon emissions when used with ultra-low sulfur fuel at 15 parts per million (ppm) or less, and these benefits are possible immediately after installation of the device.

Appropriate policy interventions can include emission standards for new vehicles that require diesel particulate filters and low sulfur fuels; measures to encourage or require retrofit of in-use vehicles with particulate filters; effective verification and enforcement regimes; and early scrappage of high polluting older vehicles. All of these strategies have been implemented successfully in several countries, and they will produce substantial local air quality and public health benefits.

Approaches that also deserve consideration are those that produce black carbon reductions and carbon dioxide reductions in tandem. These include low carbon fuels, higher efficiency engines, lighter-weight and more aerodynamic vehicles, and even zero carbon modes. For simultaneous and effective action on BC and CO2 emissions, it is important to enable rapid transition towards advanced emission control technologies and to advance renewable energy sources in all sectors to minimize trade offs and achieve climate goals in all regions. Also important are changes in transportation demand and travel behavior to reduce polluting activities. These are brought about by investments in infrastructure to support greater use of mass transit, bicycling, walking, telecommuting, and other alternative means of mobility. It is also supported by changes to land use and economic policy to encourage and facilitate these shifts without compromising mobility needs or undermining economic development. All of these approaches move transportation systems towards greater efficiency, lower cost, and fewer emissions.

Off-road transportation

Marine shipping, locomotives, agricultural vehicles, construction equipment and other commercial off-road vehicles fall under the category of off-road transportation. Emissions from these sources are less certain and likewise tend to be less stringently regulated than on-road emissions. The quality of off-road fuel also tends to be poorer. Strategies for controlling off-road emissions are similar to strategies for on-road sources, including after-treatment technologies like particulate filters enabled by lower sulfur fuel. Strategies for ships may also include operational measures like speed controls, shore-power electrification in port, and others. Marine bunker fuel used in ships contains much higher levels of sulfur than on-road fuels, however newly implemented regulations intend to reduce this by more than 80 percent by 2020. As the current suite of sulfur reduction policies improve fuel quality, concomitant reductions in black carbon are absolutely necessary to offset any potential warming impact these reductions may produce.

Residential coal and biofuel

The world's residential coal and biofuel stoves are a no-regrets target from a public health perspective, and the potential climate impacts of emissions re-enforce the need for cleaner burning stoves. Higher efficiency stoves linked with cleaner burning fuels are being developed. But strategies to address this source category face challenges in meeting local heating and cooking needs from available fuel sources with appropriate technologies. Clean and advanced renewables over the long term are particularly important in the household sector to avoid massive fossil fuel based grid expansion.

Targeted industrial sources

Unfortunately BC industrial emissions are one of the weakest parts of global emission inventories given the absence of robust field measurements. Nevertheless experts have suggested that brick kilns are the most important industrial source of BC given their predominant use of coal. BC emissions from diesel generators are captured in the off-road category of global inventories, but it is worth recognizing as well their role in industrial activities. Emissions controls will largely take place by replacing high-emitting brick kilns with alternative technologies.

Open biomass burning near snow and ice

Open burning is a high emitter of organic carbon, so its direct effect is probably cooling; however, black carbon emissions that reach snow and ice surfaces during vulnerable melt times can produce strong regional warming and melting effects. Strategies to avoid these may include the enforcement of seasonal bans on agricultural burning and other fire control practices.

RESEARCH NEEDS

Inventory measurements

Estimates of aggregate black carbon emissions such as those in the IPCC AR4 are highly uncertain. The quality of emissions information for certain source sub-groups is also poor. Ongoing inventory refinements include improvements to activity data and targeted measurements to confirm aerosol composition and quantities. This will support improved target selection and analysis.

Global warming potential

Research is needed on how the metric design depends on the formulation of climate policy. Also needed is research into the potential to expand multi-gas policies to include short-lived substances, either in the same "basket" as the long-lived forcing agents, or in a separate basket.

Climate impacts of control strategies

The net climate impact of an emission control strategy on the collection of aerosols emitted from a source is more policy relevant than the impacts of individual pollutants viewed without this context. Source-specific and geography-specific analysis of the net impacts of control strategies is needed to strengthen the case for their implementation.

Radiative forcing uncertainty

The estimate of radiative forcing since pre-industrial times given by the IPCC and more recent estimates given in the peer-reviewed literature differ by a factor of three. An explanation of this difference and consensus on the proper value would improve our understanding of the relative contribution of black carbon to global climate change.

Acknowledgements

This document was first begun in January 2009 with the input of the various speakers at the London workshop. From there, we did a full review of the IPCC Fourth assessment report and identified every mention of black carbon. All the relevant information there has been distilled and incorporated here. We also received much help and guidance from Jan Fuglestvedt and Terje Berntsen on the issue of GWPs and metrics generally. Tami Bond has been patient and generous with her time and provided substantial comments on multiple drafts. The first and subsequent drafts have been through three full rounds of comments, which amount to about 18 full sets of separate comments in track changes. They include comments from Martin Williams, Alan Lloyd, Michael Walsh, Tami Bond, Catherine Witherspoon, Mark Jacoboson, Olivier Boucher, Ellen Baum, John Guy, Jan Fuglestvedt, Drew Shindell, Elisa Dumitrescu, staff at the United Nations Environment Programme, Anumita Roy Chowdhury, Ben DeAngelo, and Kate Blumberg. Thanks go to all of them.

Notes

[1] The 2009 International Workshop on Black Carbon was organized by the International Council on Clean Transportation (ICCT) and occurred in London, UK on January 5-6. The agenda, list of speakers, and presentations are available online at http://www.theicct.org.

[2] Refers to cumulative radiative forcing on a global scale since pre-industrial times (1750-2005). Climate impacts are a consequence of radiative forcing.

[3] Refers to integrated radiative forcing, also known as the global warming potential (GWP), which is evaluated according to various forwarding-looking time horizons. The IPCC did not publish GWP values for black carbon and called for an alternative metric for short-lived forcing agents. Nevertheless it did publish the data needed to derive GWP values, which were calculated for this paper. A full discussion is given in the section on global warming potentials.

[4] The IPCC defines black carbon to include soot, charcoal and refractory organic matter, but these last two absorb from five to ten times less light per mass than soot and would have lower GWP values.

[5] Table 2.5 in Forster, P., V. Ramaswamy, P. Artaxo, et al. (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[6] Ibid Table 2.13 p 207

[7]The radiative properties of black carbon depend on its mixing state. This describes whether black carbon is incorporated within other particles (internally mixed) or separate from them (externally mixed). Model simulations and lab studies show that black carbon is predominantly internally mixed, which is associated with larger positive radiative forcing than external mixing.

[8] A pulse emission gives an instantaneous increase in the atmospheric concentration of a climate-forcing gas or aerosol.

[9] Forster et al (2007) p 211

[10] Summary report of the IPCC Expert Meeting on the Science of Alternative Metrics, 18-20 March 2009, Oslo, Norway.

[11] The time period should be oriented toward a policy goal, such as the EU target of avoiding warming greater than 2 degrees C or avoidance of tipping points like the loss of Arctic summer sea ice.

[12] International Energy Agency Energy Technology Perspectives 2008 report. Available online at http://www.iea.org/Textbase/techno/etp/index.asp