# Executive Summary

Black carbon (BC) emissions have important impacts on public health, the environment, and the Earth's climate. BC is a significant component of particle pollution, which has been linked to adverse health and environmental impacts through decades of scientific research. Recent work indicates that BC also plays an important role in climate change, although there is more uncertainty about its effects on climate than for greenhouse gases (GHG), such as carbon dioxide and methane. BC has been linked to a range of climate impacts, including increased temperatures, accelerated ice and snow melt, and disruptions to precipitation patterns. Importantly, reducing current emissions of BC may help slow the near-term rate of climate change, particularly in sensitive regions such as the Arctic. However, BC reductions cannot substitute for reductions in long-lived GHGs, which are necessary for mitigating climate change in the long run.

Despite the rapidly expanding body of scientific literature on BC, there is a need for a more comprehensive evaluation of both the magnitude of particular global and regional climate effects due to BC and the impact of emissions mixtures from different source categories. To advance efforts to understand the role of BC in climate change, on October 29, 2009, Congress requested the U.S. Environmental Protection Agency (EPA) conduct a BC study as part of *H.R. 2996: Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010.* Specifically, the legislation stated that:

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

To fulfill this charge, EPA has conducted an intensive effort to compile, assess, and summarize available scientific information on the current and future impacts of BC, and to evaluate the effectiveness of available BC mitigation approaches and technologies for protecting climate, public health, and the environment. As requested by Congress, EPA has consulted with other federal agencies on key elements of this report, including inventories, health and climate science, and mitigation options. The report draws from recent BC assessments, including work under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), the Convention on Long Range Transboundary Air Pollution (CLRTAP), and the Arctic Council. Each of these individual efforts provides important information about particular sectors, regions, or issues. The task outlined for EPA by Congress is broader and more encompassing, requiring a synthesis of currently available information about BC across numerous bodies of scientific inquiry. The results are presented in this *Report to Congress on Black Carbon*. The key messages of this report can be summarized as follows.

1. ***Black carbon is the most strongly light-absorbing component of particulate matter (PM), and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass.***

BC can be defined specifically as a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths. BC is the most effective form of PM, by mass, at absorbing solar energy;

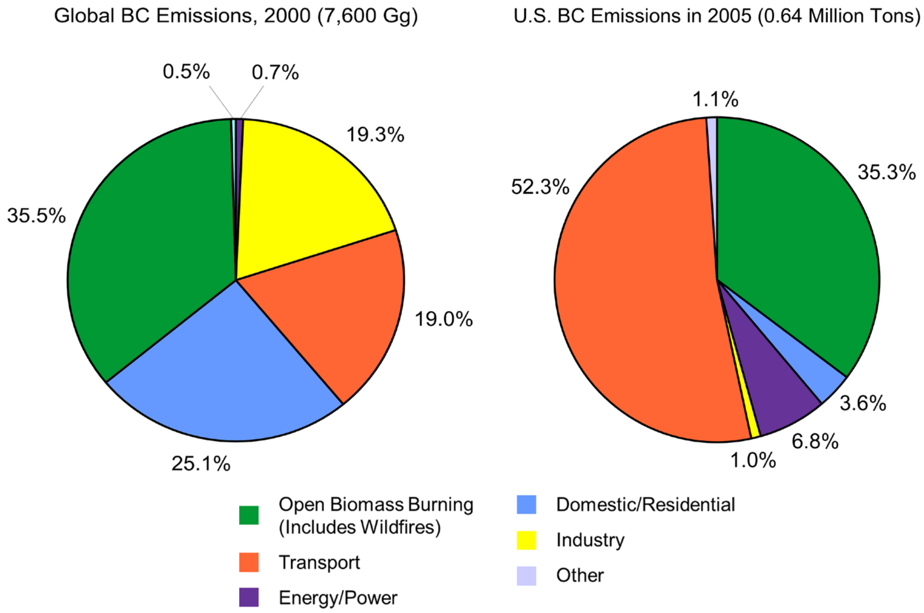


**Figure A. BC Emissions by Major Source Category.** (Source: Lamarque et al., 2010 and U.S. EPA)

other types of particles, including sulfates, nitrates and organic carbon (OC), generally reflect light. BC is a major component of "soot," a complex light-absorbing mixture that also contains organic carbon. Recent estimates of BC emissions by source category in the United States and globally are shown in Figure A.

2. ***BC is emitted directly into the atmosphere in the form of fine particles ($PM_{2.5}$). The United States contributes about 8% of the global emissions of BC. Within the United States, BC is estimated to account for approximately 12% of all direct $PM_{2.5}$ emissions in 2005. Many countries have significantly higher $PM_{2.5}$ emissions than the United States, and countries with a different portfolio of emissions sources might have a significantly higher percentage of BC.***

3. ***BC contributes to the adverse impacts on human health, ecosystems, and visibility associated with $PM_{2.5}$.***

Short-term and long-term exposures to $PM_{2.5}$ are associated with a broad range of human health impacts, including respiratory and cardiovascular effects, as well as premature death. $PM_{2.5}$, both ambient and indoor, is estimated to result in millions of premature deaths worldwide, the majority of which occur in developing countries. The World Health Organization estimates that indoor smoke from solid fuels is the 10$^{th}$ major mortality risk factor globally, contributing to approximately 2 million deaths annually. Women and children are particularly at risk. Ambient air pollution is also a significant health threat: according to the WHO, urban air pollution is among the top ten risk factors in medium- and high-income countries. Urban air pollution is not ranked in the top ten major risk factors in low-income countries since other risk factors (e.g., childhood underweight and unsafe water, sanitation and hygiene) are so substantial; however, a much larger portion of the total deaths related to ambient $PM_{2.5}$ globally are expected to occur in developing regions, partly due to the size of exposed populations in those regions. $PM_{2.5}$ is also linked to adverse impacts on ecosystems, to visibility impairment, to reduced agricultural production in some parts of the world, and to materials soiling and damage.

Over the past decade, the scientific community has focused increasingly on trying to identify the health impacts of particular $PM_{2.5}$ constituents, such as BC. However, EPA has determined that there is insufficient information at present to differentiate the health effects of the various constituents of $PM_{2.5}$; thus, EPA assumes that many constituents are associated with adverse health impacts. It is noteworthy that emissions and ambient concentrations of directly emitted $PM_{2.5}$ are often highest in urban areas, where large numbers of people live.

***4. BC influences climate through multiple mechanisms:***

- *Direct effect:* BC absorbs both incoming and outgoing radiation of all wavelengths, which contributes to warming of the atmosphere and dimming at the surface.
- *Snow/ice albedo effect:* BC deposited on snow and ice darkens the surface and decreases reflectivity, thereby increasing absorption and accelerating melting.
- *Other effects:* BC also alters the properties of clouds, affecting cloud reflectivity and lifetime ("indirect effects"), stability ("semi-direct effect") and precipitation.

***5. The direct and snow/ice albedo effects of BC are widely understood to lead to climate warming. However, the globally averaged net climate effect of BC also includes the effects associated with cloud interactions, which are not well quantified and may cause either warming or cooling. Therefore, though most estimates indicate that BC has a net warming influence, a net cooling effect cannot be ruled out. It is also important to note that the net radiative effect of all aerosols combined (including sulfates, nitrates, BC and OC) is widely understood to be negative (cooling) on a global average basis.***

*The direct radiative forcing effect of BC is the best quantified and appears to be positive and significant*

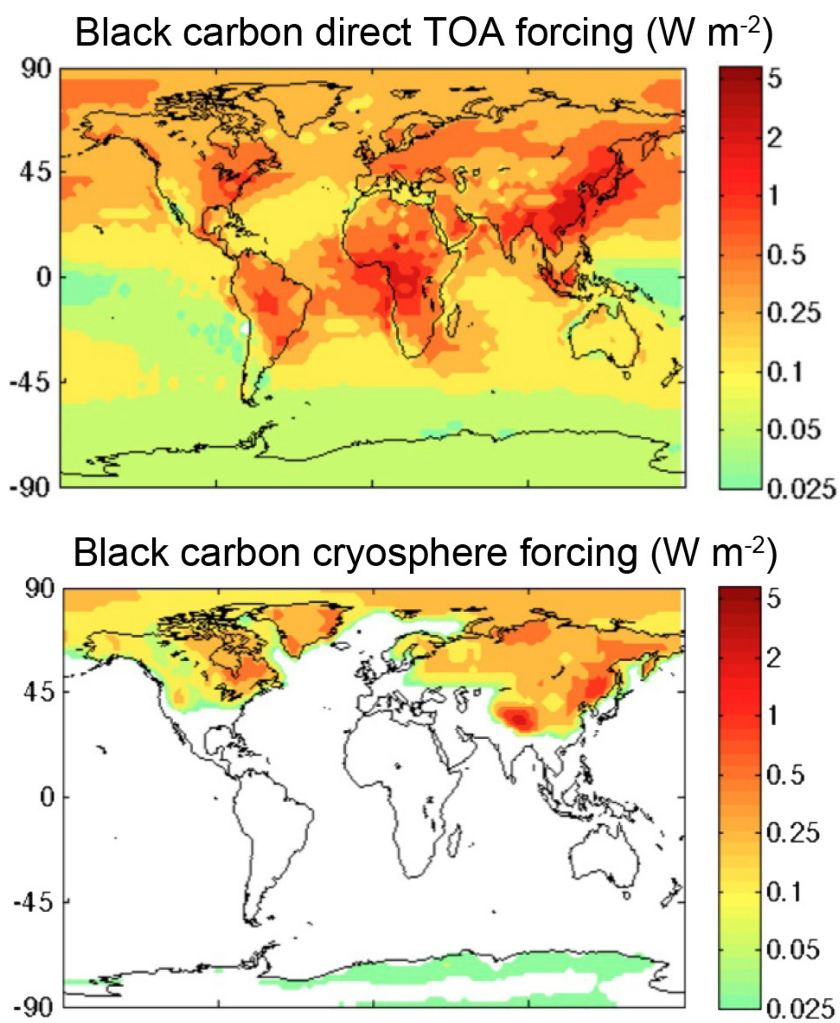


**Figure B. Regional Variability in Direct Radiative Forcing and Snow/Ice Albedo Forcing for BC from All Sources,** simulated with the Community Atmosphere Model. (Source: Bond et al., 2011) *on both global and regional scales. This warming effect is augmented by deposition of BC on snow and ice.* These effects are shown in Figure B. The central estimates of global average direct forcing by BC from surveyed studies range from +0.34 to +1.0 Watts per square meter (W $m^{-2}$). A recent UNEP/WMO assessment presented a narrower central range of +0.3 to +0.6 W $m^{-2}$. These estimates are generally higher than the 2007 Intergovernmental Panel on Climate Change (IPCC) estimate of +0.34 (±0.25) W $m^{-2}$.

The snow/ice albedo effect from BC has been estimated in recent studies to add about +0.05 W $m^{-2}$, generally less than the +0.1 (±0.1) W $m^{-2}$ estimated by the IPCC; however, UNEP/WMO found that when the snow/ice albedo forcing estimates are adjusted to account for the greater warming efficacy of the snow/ice deposition mechanism, the snow/ice albedo effect could add +0.05 to +0.25 W $m^{-2}$ of forcing. The sum of the direct and snow/ice albedo effects of BC on the global scale is likely comparable to or larger than the forcing effect from methane, but less than the effect of carbon dioxide;[1] however, there is more uncertainty in the forcing estimates for BC.

*The climate effects of BC via interactions with clouds are more uncertain, and their net climate influence is not yet clear.* All aerosols (including BC) affect climate indirectly by changing the reflectivity (albedo) and lifetime of clouds. The net indirect effect of all aerosols is very uncertain but is thought to have a net cooling influence. The IPCC estimated the global average cloud albedo forcing from all aerosols as -0.7 W $m^{-2}$ (with a 5 to 95% confidence range of -0.3 W $m^{-2}$ to -1.80 W $m^{-2}$). The IPCC did not provide quantitative estimates of the effect of aerosols on cloud lifetime, and the contribution of BC to these indirect effects has not been explicitly quantified to date. BC has additional effects on clouds—including changes to cloud stability and enhanced precipitation from colder clouds—that can lead to either warming or cooling. However, few quantitative estimates of these effects are available, and significant uncertainty remains. Due to all of the remaining gaps in scientific knowledge, it is difficult to place quantitative bounds on the forcing attributable to BC impacts on clouds at present; however, UNEP/WMO have provided a central forcing estimate of -0.4 to +0.4 W $m^{-2}$ for all of the cloud effects of BC combined.

*The sign and magnitude of the net climate forcing from BC emissions are not fully known at present, largely due to remaining uncertainties regarding the effects of BC on clouds.* There is inconsistency among reported observational and modeling results, and many studies do not provide quantitative estimates of cloud impacts. In the absence of a full quantitative assessment, the current scientific basis for understanding BC climate effects is incomplete. Based on a limited number of modeling studies, the recent UNEP/WMO assessment estimated that global average net BC forcing is likely to be positive and in the range of 0.0 to +1.0 W $m^{-2}$, with a best estimate of +0.6 W $m^{-2}$; however, further work is needed to refine these estimates.

6. ***Sensitive regions such as the Arctic and the Himalayas are particularly vulnerable to the warming and melting effects of BC.***

Studies have shown that BC has especially strong impacts in the Arctic, contributing to earlier spring melting and sea ice decline. All particle mixtures reaching the Arctic are a concern, because even emissions mixtures that contain more reflective (cooling) aerosols can lead to warming if they are darker than the underlying ice or snow. Studies indicate that the effect of BC on seasonal snow cover duration in some regions can be substantial, and that BC deposited on ice and snow will continue to have radiative effects as long as the BC remains exposed (until the snow melts away or fresh snow falls). BC has also been shown to be a significant factor in the observed increase in melting rates of some glaciers and snowpack in parts of the Hindu Kush-Himalayan-Tibetan (HKHT) region (the "third pole").

7. ***BC contributes to surface dimming, the formation of Atmospheric Brown Clouds (ABCs), and changes in the pattern and intensity of precipitation.***

The absorption and scattering of incoming solar radiation by BC and other particles cause surface dimming by reducing the amount of solar radiation reaching the Earth's surface. In some regions, especially Asia, southern Africa, and the Amazon Basin, BC, sulfates, organics, dust and other components combine to form pollution clouds known as Atmospheric Brown Clouds (ABCs). ABCs have been linked to surface dimming and a decrease in vertical mixing, which exacerbates air pollution episodes. ABCs also contribute to changes in the pattern and intensity of rainfall, and to observed changes in monsoon circulation in South Asia. In general, regional changes in precipitation due to BC and other aerosols are likely to be highly variable, with some regions seeing increases while others experience decreases.

[1] The IPCC's radiative forcing estimates for elevated concentrations of $CO_2$ and methane are +1.66 W $m^{-2}$ and +0.48 W $m^{-2}$, respectively.

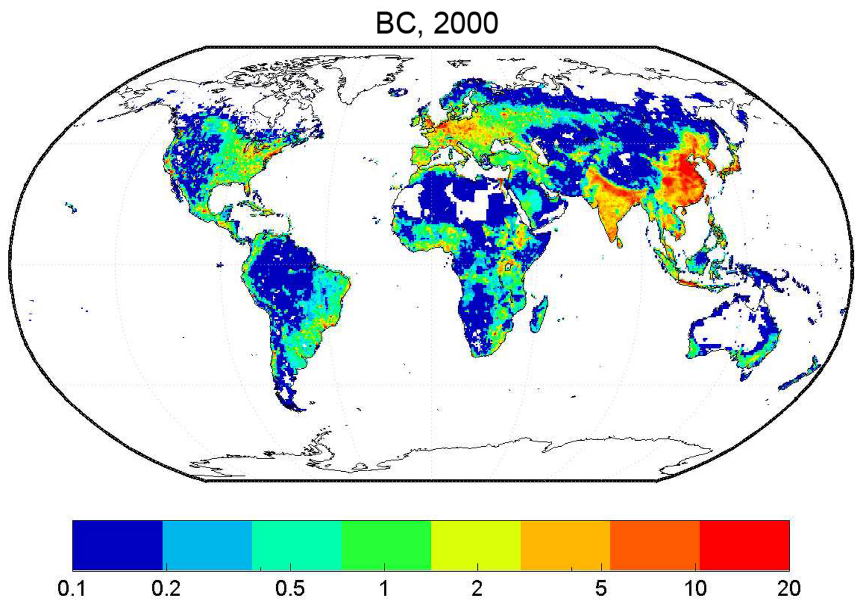


**Figure C. BC Emissions, 2000, Gg.** (Courtesy of Tami Bond, produced based on data from Bond et al., 2007)

8. ***BC is emitted with other particles and gases, many of which exert a cooling influence on climate. Therefore, estimates of the net effect of BC emissions sources on climate should include the offsetting effects of these co-emitted pollutants. This is particularly important for evaluating mitigation options. Some combustion sources emit more BC than others relative to the amount of co-pollutants; reductions from these sources have the greatest likelihood of providing climate benefits.***

The same combustion processes that produce BC also produce other pollutants, such as sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), OC and $CO_2$. Some of these co-emitted pollutants result in "scattering" or reflecting particles (e.g. sulfate, nitrate, OC) which exert a cooling effect on climate. The sign and magnitude of the forcing resulting from particular emissions mixtures depend on their composition. For example, the particles emitted by mobile diesel engines are about 75% BC, while particle emissions from biomass burning are dominated by OC. Sources rich in BC have a greater likelihood of contributing to climate warming, and this may affect climate-related mitigation choices. Although OC generally leads to cooling, some portion of co-emitted OC, notably brown carbon (BrC), partially absorbs solar radiation. The net contribution of BrC to climate is presently unknown.

Atmospheric processes that occur after BC is emitted, such as mixing, aging, and coating, can also affect the net influence on climate.

9. ***BC's short atmospheric lifetime (days to weeks), combined with its strong warming potential, means that targeted strategies to reduce BC emissions can be expected to provide climate benefits within the next several decades.***

*Because the duration of radiative forcing by BC is very limited, the climate will respond quickly to BC emissions reductions, and this can help slow the rate of climate change in the near term.* In contrast, long-lived GHGs may persist in the atmosphere for centuries. Therefore, reductions in GHG emissions will take longer to influence atmospheric concentrations and will have less impact on climate on a short timescale. However, since GHGs are the largest contributor to current and future climate change, and because GHGs accumulate in the atmosphere, deep reductions in these pollutants are necessary for limiting climate change over the long-term.

*Emissions sources and ambient concentrations of BC vary geographically and temporally* (Figure C), resulting in climate effects that are more regional and seasonal than the more uniform effects of long-lived, well-mixed GHGs. Likewise, mitigation actions for BC will produce different climate results depending on the region, season, and sources in the area where emissions reductions occur.

***10. The different climate attributes of BC and long-lived GHGs make it difficult to interpret comparisons of their relative climate impacts based on common metrics.***

Due in large part to the difference in lifetime between BC and $CO_2$, a comparison between the relative climate impacts of BC and $CO_2$ (or other climate forcers) is very sensitive to the metric used. There is currently no single metric (e.g., Global Warming Potential or GWP) that is widely accepted by the science and research community for this purpose. However, new metrics designed specifically for short-lived climate forcers like BC have recently been developed, and these metrics may enable better prioritization among mitigation options with regard to potential net climate effects.

***11. Based on recent emissions inventories (2000 for global and 2005 for the United States), the majority of global BC emissions come from Asia, Latin America, and Africa. The United States currently accounts for approximately 8% of the global total, and this fraction is declining. Emissions patterns and trends across regions, countries and sources vary significantly.***

Though there is significant uncertainty in global BC emissions inventories, recent studies indicate that global BC emissions have been increasing for many decades. However, emissions of BC in North America and Europe have declined substantially since the early 1900s and are expected to decline further in the next several decades due to pollution controls and use of cleaner fuels. Elsewhere, BC emissions have been increasing, with most of the increase coming from developing countries in Asia, Africa and Latin America. According to available estimates, these regions currently contribute more than 75% of total global BC emissions, with the majority of emissions coming from the residential sector (cookstoves) and open biomass burning. Current emissions from the United States, OECD Europe, the Middle East, and Japan come mainly from the transportation sector, particularly from mobile diesel engines. In the United States, nearly 50% of BC emissions came from mobile diesel engines in 2005.

***12. Control technologies are available to reduce BC emissions from a number of source categories.***

BC emissions reductions are generally achieved by applying technologies and strategies to improve combustion and/or control direct $PM_{2.5}$ emissions from sources. Though the costs of such mitigation approaches vary, many reductions can be achieved at reasonable costs. Controls applied to reduce BC will help reduce total $PM_{2.5}$ and other co-pollutants.

***13. BC mitigation strategies, which lead to reductions in fine particles, can provide substantial public health and environmental benefits.***

Strategies to reduce BC generally lead to reductions in emissions of all particles from a particular source. Thus, while it is not easy to reduce BC in isolation from other constituents, most mitigation strategies will provide substantial benefits in the form of $PM_{2.5}$ reductions. Reductions in directly emitted $PM_{2.5}$ can substantially reduce human exposure, providing large public health benefits that often exceed the costs of control. In the United States, the average public health benefits associated with reducing directly emitted $PM_{2.5}$ are estimated to range from $290,000 to $1.2 million per ton $PM_{2.5}$ in 2030 (2010$). The cost of the controls necessary to achieve these reductions is generally far lower. For example, the costs of PM controls for new diesel engines are estimated to be about $14,000 per ton $PM_{2.5}$ (2010$). BC reduction strategies implemented at the global scale could provide very large benefits: the $PM_{2.5}$ reductions resulting from BC mitigation measures could potentially result in hundreds of thousands of avoided premature deaths each year.

***14. Mitigating BC can also make a difference in the short term for climate, at least in sensitive regions.***

Benefits in sensitive regions like the Arctic, or in regions of high emissions such as Asia, may include reductions in warming and melting (ice, snow, glaciers) and reversal of changes in precipitation patterns. BC reductions could help reduce the rate of warming soon after they are implemented. However, available studies also suggest that BC mitigation alone would be insufficient to change the long-term trajectory of global warming (which is driven by GHGs).

***15. Selecting optimal BC mitigation measures requires taking into account the full suite of impacts and attempting to maximize co-benefits and minimize unintended consequences across all objectives (health, climate, and environment).***

With a defined set of goals, policymakers can evaluate the “mitigation potential” within each country or region. The mitigation potential depends on total BC emissions and key emitting sectors, and also depends on the availability of control technologies or alternative mitigation strategies.

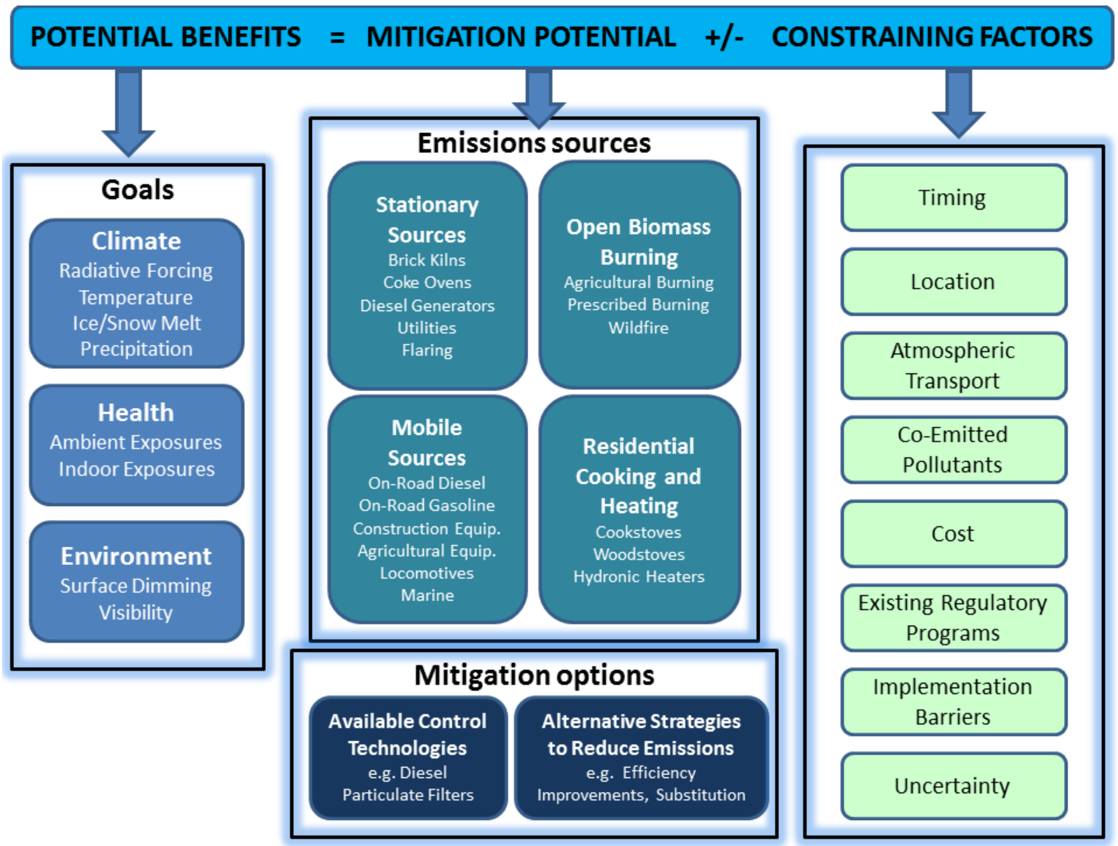


**Figure D. Policy Framework for Black Carbon Mitigation Decisions.** (Source: U.S. EPA.)

As illustrated in Figure D, the ideal emissions reduction strategies will also depend on a range of constraining factors, including:

- Timing
- Location
- Atmospheric Transport
- Co-emitted Pollutants
- Cost
- Existing Regulatory Programs
- Implementation Barriers
- Uncertainty

***16. Considering the location and timing of emissions and accounting for co-emissions will improve the likelihood that mitigation strategies will be properly guided by the balance of climate and public health objectives.***

PM mitigation strategies that focus on sources known to emit large amounts of BC—especially those with a high ratio of BC to OC, like diesel emissions—will maximize climate co-benefits. The timing and location of the reductions are also very important. Some of the most significant climate benefits of BC-focused control strategies may come from reducing emissions affecting the Arctic, Himalayas and other ice and snow-covered regions.

The effect of BC emissions reductions on human health is a function of changing exposure and the size of the affected population. The largest health benefits from BC-focused control strategies will occur locally near the emissions source and where exposure affects a large population.

***17. Achieving further BC reductions, both domestically and globally, will require adding a specific focus on reducing direct $PM_{2.5}$ emissions to overarching fine particle control programs.***

BC reductions that have occurred to date (largely in developed countries) are mainly due to control programs aimed at $PM_{2.5}$, not targeted efforts to reduce BC per se. Greater attention to BC-focused strategies has the potential to help protect the climate (via the BC reductions achieved through direct $PM_{2.5}$ controls) while ensuring continued improvements in public health (via control of direct $PM_{2.5}$ in highly populated areas). Even if such controls are more costly than controls on secondary PM precursors, the combined public health and climate benefits may justify the expense.

***18. The most promising mitigation options identified in this report for reducing BC (and related "soot") emissions are consistent with control opportunities emphasized in other recent assessments.***

- **United States:** *The United States will achieve substantial BC emissions reductions by 2030, largely due to controls on new mobile diesel engines. Diesel retrofit programs for in-use mobile sources are a valuable complement to new engine standards for reducing emissions. Other source categories in the United States, including stationary sources (industrial, commercial and institutional boilers, stationary diesel engines, uncontrolled coal-fired electric generating units), residential wood combustion (hydronic heaters and woodstoves), and open biomass burning also offer potential opportunities but have more limited mitigation potential due to smaller remaining emissions in these categories, or limits on the availability of effective BC control strategies.*

  – Total **mobile source** BC emissions are projected to decline by 86% by 2030 due to regulations already promulgated. BC emissions from mobile diesel engines (including on-road, non road, locomotive, and commercial marine engines) in the United States are being controlled through two primary mechanisms: (1) *emissions standards for new engines*, including requirements resulting in use of diesel particulate filters (DPFs) in conjunction with ultra low sulfur diesel fuel; and (2) retrofit programs for *in-use mobile diesel engines*, such as EPA's National Clean Diesel Campaign and the SmartWay Transport Partnership Program. Substantial future reductions in mobile diesel emissions are anticipated through new engine requirements and diesel retrofit programs.

  – BC emissions from **stationary sources** in the United States have declined dramatically in the last century, with remaining emissions coming primarily from coal combustion (utilities, industrial/commercial boilers, other industrial processes) and stationary diesel engines. Available control technologies and strategies include use of cleaner fuels and direct $PM_{2.5}$ reduction technologies such as fabric filters (baghouses), electrostatic precipitators (ESPs), and DPFs.

  – Emissions of all pollutants from **residential wood combustion** (RWC) are currently being evaluated as part of EPA's ongoing review of emissions standards for residential wood heaters, including hydronic heaters, woodstoves, and furnaces. Mitigation options include providing alternatives to wood, replacing inefficient units or retrofitting existing units.

  – **Open biomass burning,** including both prescribed fires and wildfires, represents a potentially large but less certain portion of the U.S. BC inventory. These sources emit much larger amounts of OC compared to BC. The percent of land area affected by different types of burning is uncertain, as are emissions estimates. Appropriate mitigation measures depend on the timing and location of burning, resource management objectives, vegetation type, and available resources. For wildfires, expanding domestic fire prevention efforts may help to reduce BC emissions.

- **Global:** *The most important BC emissions reduction opportunities globally include residential cookstoves in all regions; brick kilns and coke ovens in Asia; and mobile diesels in all regions. A variety of other opportunities may exist in individual countries or regions.*

  – Other developed countries have emissions patterns and control programs that are similar to the United States, though the timing of planned emissions reductions may vary. Developing countries have a higher concentration of emissions in the residential and industrial sectors, but the growth of the mobile source sector in these countries may lead to an increase in their overall BC emissions and a shift in the relative importance of specific BC-emitting sources over the next several decades.

  – For **mobile sources**, both new engine standards and retrofits of existing engines/vehicles may help reduce BC emissions in the future. While many other countries have already begun phasing in emissions and fuel standards, BC emissions in this category in developing countries are expected to continue to increase. Emissions control requirements lag behind in some regions, as does on-the-ground deployment of DPFs and low sulfur fuels. Further or more rapid reductions in BC will depend on accelerated deployment of clean engines and fuels.

– Emissions from **residential cookstoves** are both a large source of BC globally and a major threat to public health. Approximately 3 billion people worldwide cook their food or heat their homes by burning biomass or coal in rudimentary stoves or open fires, resulting in pollution exposures that lead to 2 million deaths each year. Mitigation in this sector represents the area of largest potential public health benefit of any of the sectors considered in this report. Significant expansion of current clean cookstove programs would be necessary to achieve large-scale climate and health benefits. A wide range of improved stove technologies is available, but the potential climate and health benefits vary substantially by technology and fuel. Setting BC emissions reductions as a policy priority would drive cookstove efforts toward solutions that achieve this goal. A number of factors point to much greater potential to achieve large-scale success in this sector today.

– The largest **stationary sources** of BC emissions internationally include brick kilns, coke ovens (largely from iron/steel production), and industrial boilers. Replacement or retrofit options already exist for many of these source categories.

– **Open biomass burning** is the largest source of BC emissions globally. However, emissions of OC (including potentially light absorbing BrC) are approximately seven times higher than BC emissions from this sector, and more complete emissions inventory data are needed to characterize impacts of biomass burning and evaluate the effectiveness of mitigation measures at reducing BC. Expanded wildfire prevention efforts may help to reduce BC emissions globally. Successful implementation of mitigation approaches in world regions where biomass burning is widespread will require training in proper burning techniques and tools to ensure effective use of prescribed fire.

- **Sensitive Regions:** To address impacts in the Arctic, other assessments have identified the transportation sector (land-based diesel engines and Arctic shipping); residential heating (wood-fired stoves and boilers); and forest, grassland and agricultural burning as primary mitigation opportunities. In the Himalayas, studies have focused on residential cooking; industrial sources (especially coal-fired brick kilns); and transportation, primarily on-road and off-road diesel engines.

***19. A variety of other options may also be suitable and cost-effective for reducing BC emissions, but these can only be identified with a tailored assessment that accounts for individual countries' resources and needs.***

Some potential sectors of interest for further exploration include agricultural burning, oil and gas flaring, and stationary diesel engines in the Arctic far north.

***20. Despite some remaining uncertainties about BC that require further research, currently available scientific and technical information provides a strong foundation for making mitigation decisions to achieve lasting benefits for public health, the environment, and climate.***