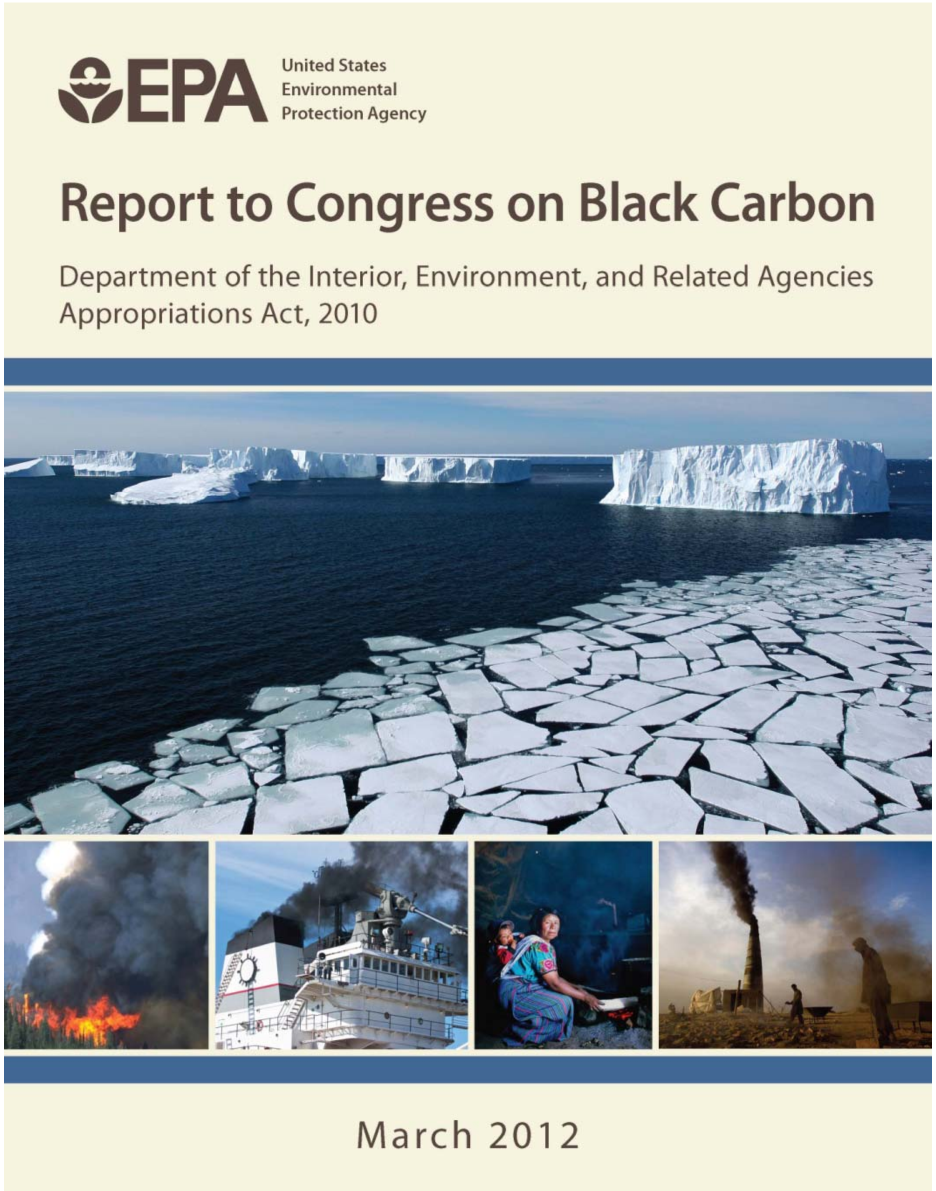
Report to Congress on Black Carbon

Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010

March 30, 2012

October 2009 Interior Appropriations Bill Requirement

- "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:
  - an <u>inventory</u> of the major sources of black carbon;
  - an assessment of the <u>impacts</u> of black carbon on global and regional climate;
  - an assessment of potential <u>metrics</u> 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 <u>cost-effective approaches</u> to reduce black carbon emissions; and
  - an analysis of the climatic effects and other environmental and public health <u>benefits</u> of those approaches."

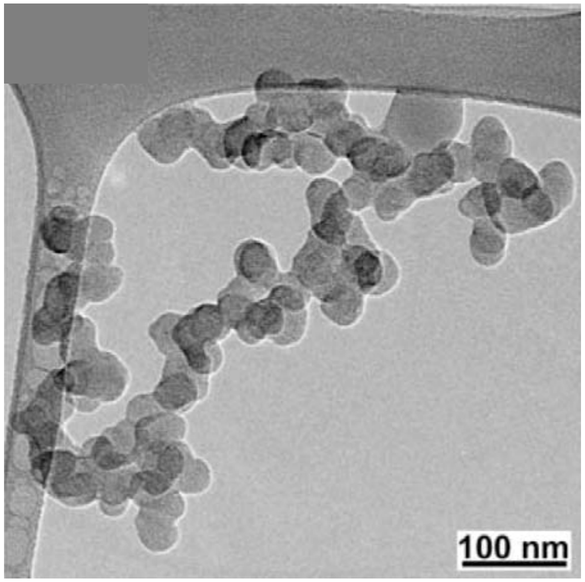


The Report:

- Defines black carbon (BC) and describes its role in climate change.
- Characterizes the full impacts of BC on climate, public health, and the environment based on recent scientific studies.
- Summarizes data on domestic and global BC emissions, ambient concentrations, deposition, and trends.
- Discusses currently available mitigation approaches and technologies for four main sectors:
  - Mobile Sources
  - Stationary Sources
  - Residential Cooking and Heating
  - Open Biomass Burning
- Considers the potential benefits of BC mitigation for climate, public health, and the environment.

Highlights, Executive Summary and Full Report available online at: www.epa.gov/blackcarbon

What is Black Carbon?

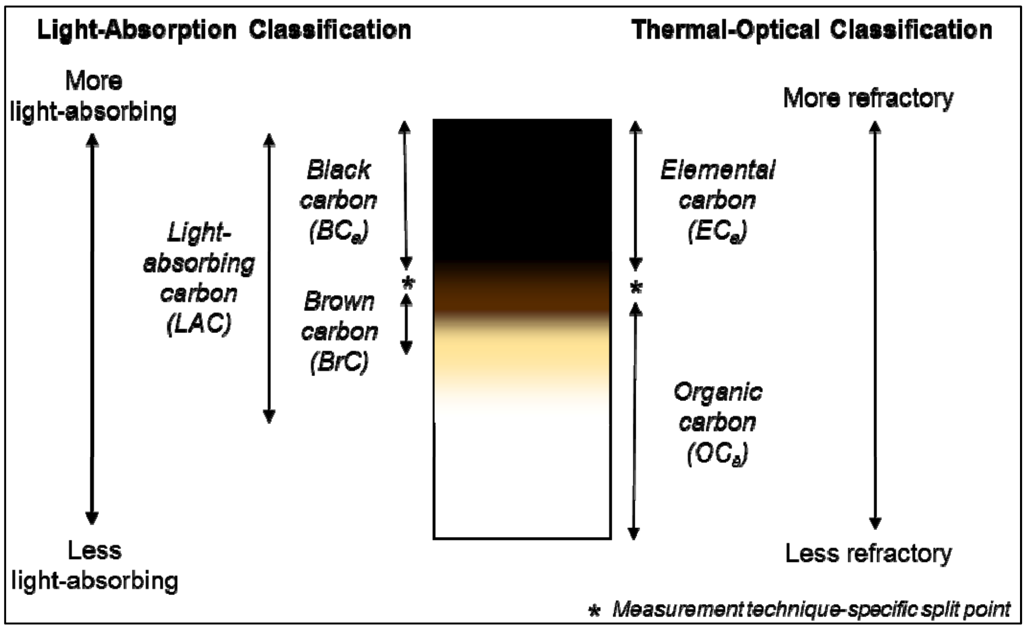


- Black carbon is the most strongly light-absorbing component of particulate matter (PM).
  - BC is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths.
- Other types of particles, including sulfates, nitrates and organic carbon (OC), generally reflect light.

- BC is formed by incomplete combustion of fossil fuels, biofuels, and biomass.
- BC is emitted directly into the atmosphere in the form of fine particles (i.e., “direct $PM_{2.5}$”).
- BC is a major component of “soot”, a complex light-absorbing mixture that also contains organic carbon.

Black Carbon Measurement

- Estimates of BC are made with a variety of instrumentation and measurement techniques.
  - Most ground level estimates of BC are reported as mass concentrations based on thermal-optical (EC) and filter-based optical (BC) techniques.
  - BC and EC values from these measurement methods are highly correlated.
- The U.S. has recently standardized BC measurements for its major routine speciation monitoring networks.



Terminology

Black carbon (BC) is 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, and is produced by incomplete combustion.

Organic carbon (OC) generally refers to the mix of compounds containing carbon bound with other elements like hydrogen or oxygen. OC may be a product of incomplete combustion, or formed through the oxidation of VOCs in the atmosphere.[2] Both primary and secondary OC possess radiative properties that fall along a continuum from light-absorbing to light-scattering.

Brown carbon (BrC) refers to a class of OC compounds that absorb ultraviolet (UV) and visible solar radiation. Like BC, BrC is a product of incomplete combustion.[3]

Carbonaceous PM includes BC and OC. Primary combustion particles are largely composed of these materials.

Light absorbing carbon (LAC) consists of BC plus BrC.

Soot, a complex mixture of mostly BC and OC, is the primary light-absorbing pollutant emitted by the incomplete combustion of fossil fuels, biofuels, and biomass.

Measurement of the Carbonaceous Components of Particles

LEFT: Black carbon and other types of light-absorbing materials can be characterized by measuring their specific light-absorbing properties (BCa/BrC/LAC).

RIGHT: Other approaches characterize particles by measuring the refractory nature of the material (inertness at high temperatures) (ECa and OCa).

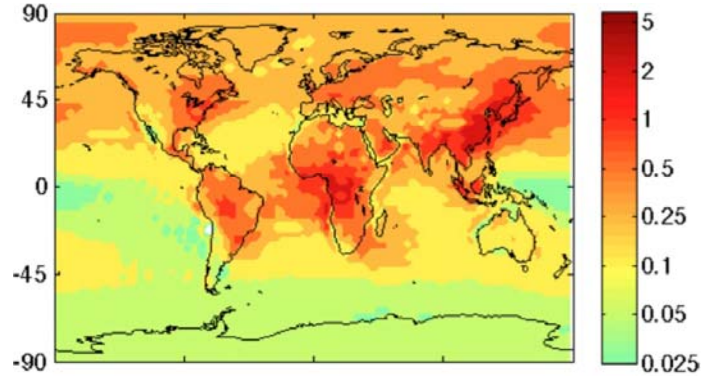
Climate Effects of Black Carbon

- BC influences climate by:
  - directly absorbing light (⇒ warming)
  - reducing the reflectivity ("albedo") of snow and ice through deposition (⇒ warming)
  - interacting with clouds (⇒ cooling and/or warming)

- BC's climate impacts likely include increased global average temperatures and accelerated ice/snow melt.
  - The direct and snow/ice albedo effects are widely understood to be warming; however, cloud effects are highly uncertain and net impact on climate is unclear.

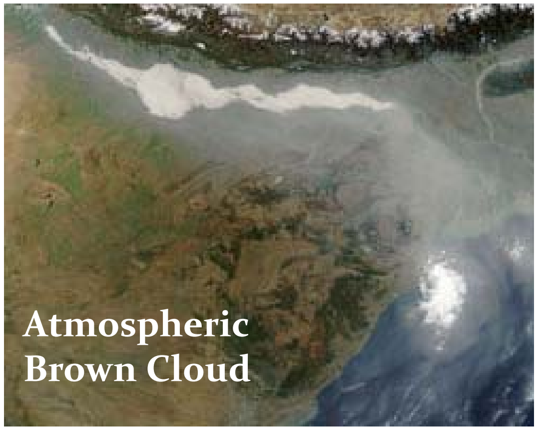
- Sensitive regions such as the Arctic and the Himalayas are particularly vulnerable to warming/melting effects of BC.

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



Global Direct Forcing due to Black Carbon
(Watts per square meter, from Bond. et al., 2007)

Deposition on Snow/Ice



NASA Goddard Space Flight Center/Jeff Schmaltz

Health and Environmental Effects of Black Carbon

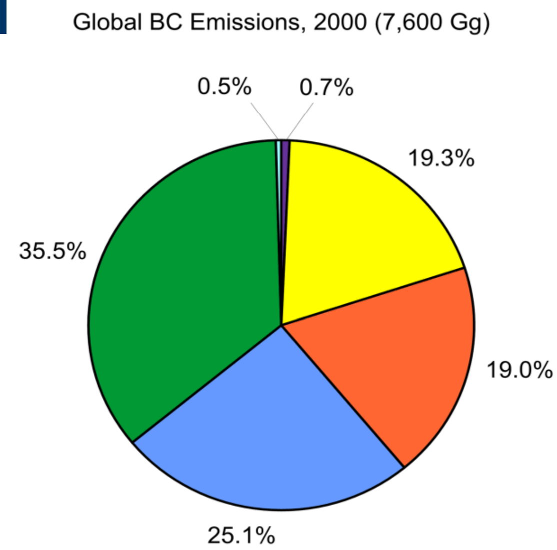
Brick Kiln in Kathmandu

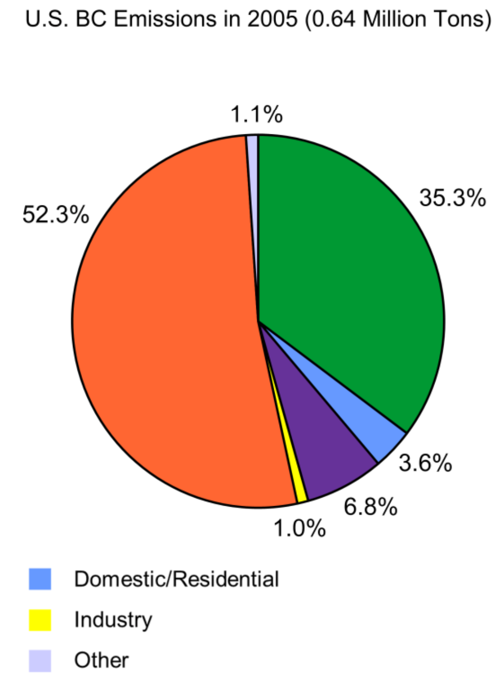
- BC contributes to the adverse impacts on human health, ecosystems, and visibility associated with $PM_{2.5}$.
- Short-term and long-term exposures to $PM_{2.5}$ are associated with a broad range of human health impacts, including respiratory and cardiovascular effects and premature death.
- The World Health Organization (WHO) estimates that indoor smoke from solid fuels is among the top ten major mortality risk factors globally, contributing to approximately 2 million deaths each year (mainly among women and children).
- Ambient particle pollution is also a significant health threat in both developed and developing countries. Emissions and ambient concentrations of directly emitted $PM_{2.5}$ are often highest in urban areas, where large numbers of people live.
- $PM_{2.5}$, including BC, is linked to adverse impacts on ecosystems, to visibility impairment, to reduced agricultural production in some regions, and to materials soiling and damage.

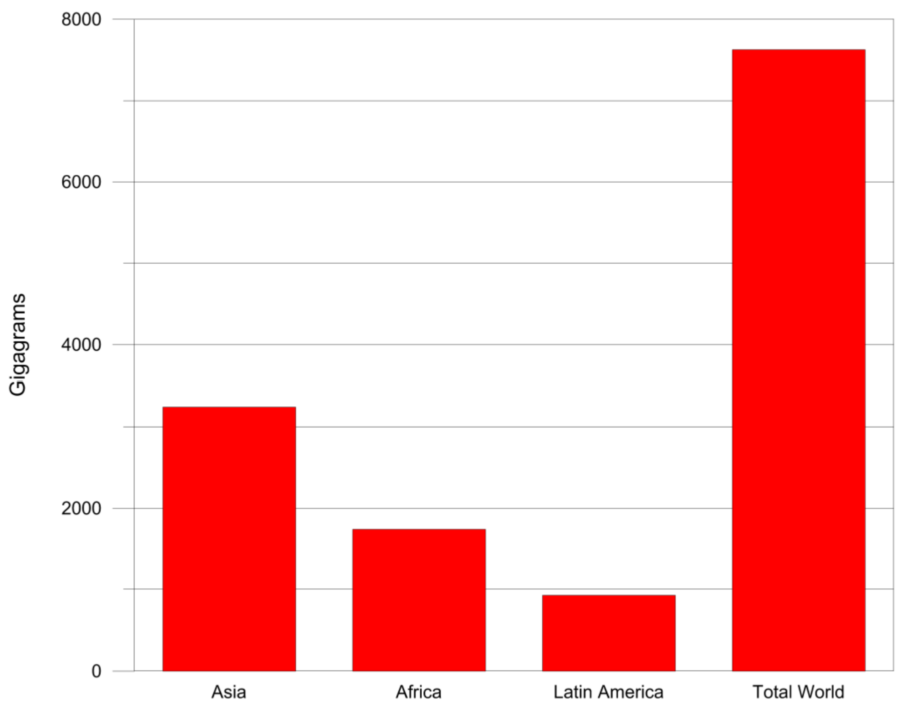
Traditional Cookstove in India

Black Carbon Emissions

- U.S. 2005 BC emissions = 640,000 tons, or approximately 12% of all direct $PM_{2.5}$ emissions nationwide.
- Mobile sources are the largest U.S. BC emissions category.
  - Diesel engines and vehicles account for 93% of mobile source BC emissions.







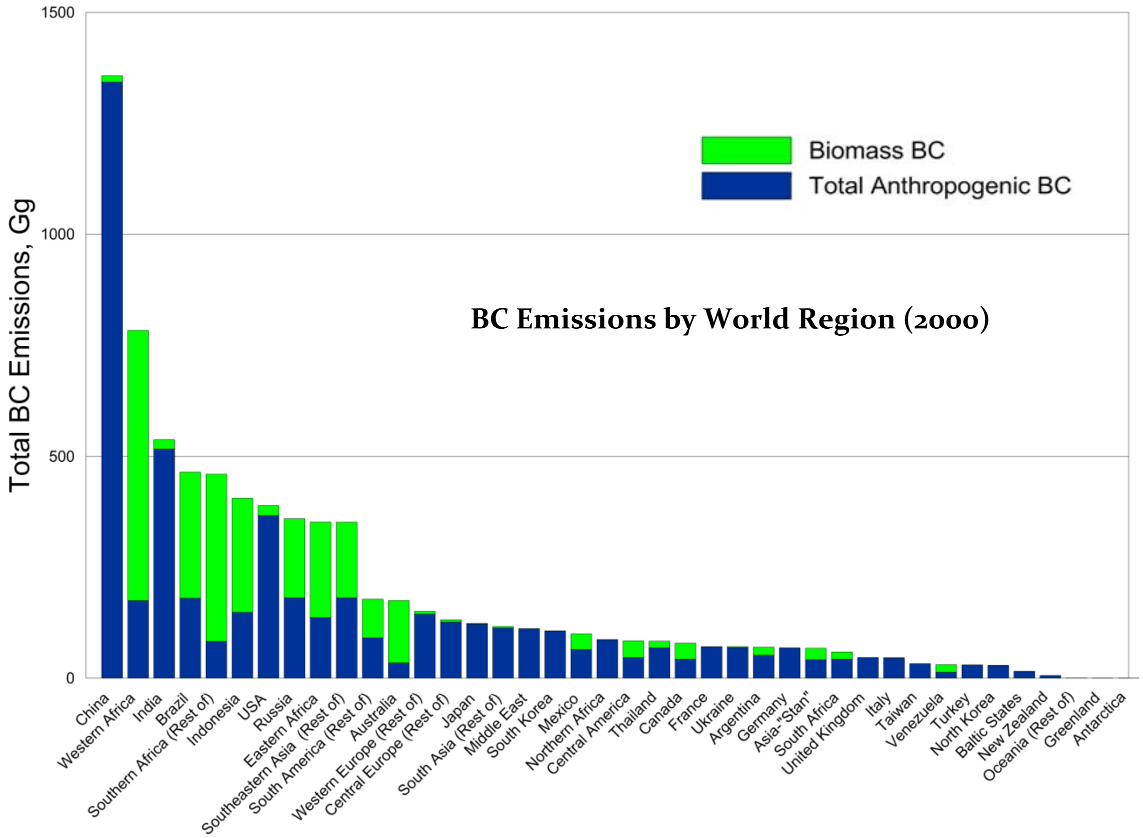
Aggregate BC Emissions in Selected World Regions (2000)

- Globally, the majority (75%) of global BC emissions come from Asia, Africa and Latin America.
- 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.

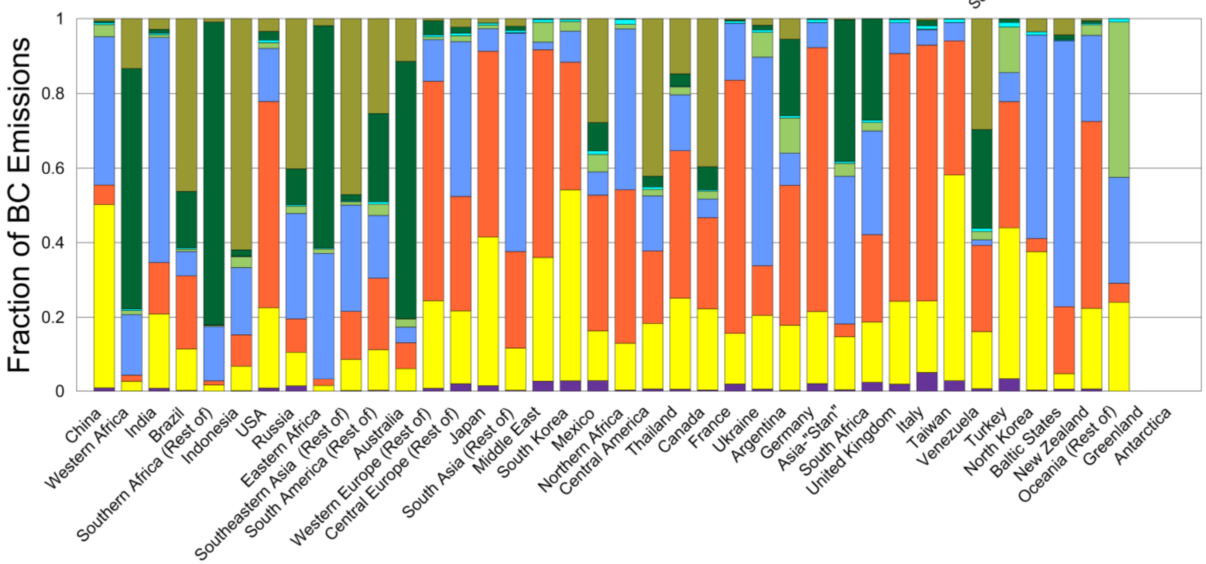
Regional Variability in Black Carbon Emissions

- In developing countries, biomass burning and residential sources (i.e., cookstoves) are the dominant sources of BC.

- In developed countries, emissions of BC are dominated by transportation and industry.



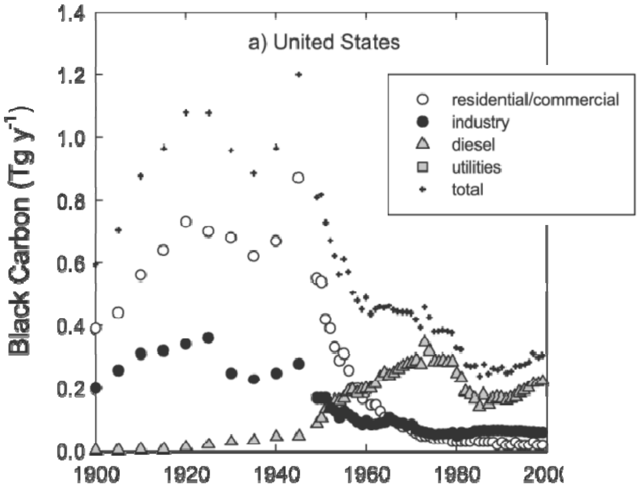
BC Emissions by World Region (2000)

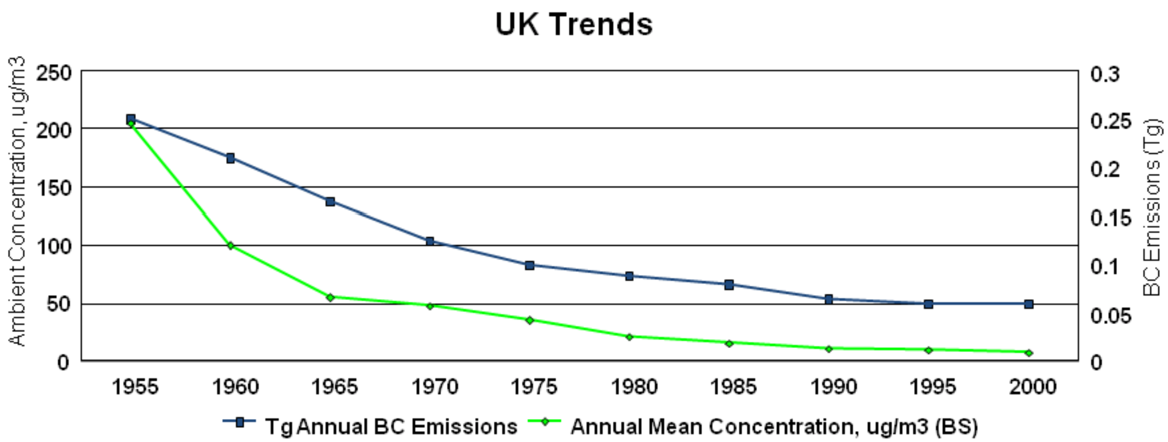


Fraction of BC Emissions from Different Emissions Source Categories, by World Region (2000)

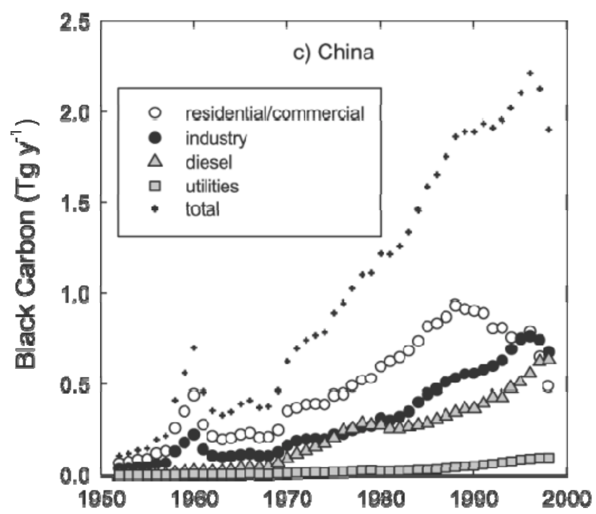
Black Carbon Emissions: Trends

- Long-term historic trends of BC emissions in the United States and other developed countries reveal a steep decline in emissions over the last several decades.
- Ambient BC concentrations have declined as emissions have been reduced.





- Developing countries (e.g., China and India) have shown a very sharp rise in BC emissions over the past 50 years.
- Total global BC emissions are likely to decrease in the future, but developing countries may experience emissions growth in key sectors (transportation, residential).

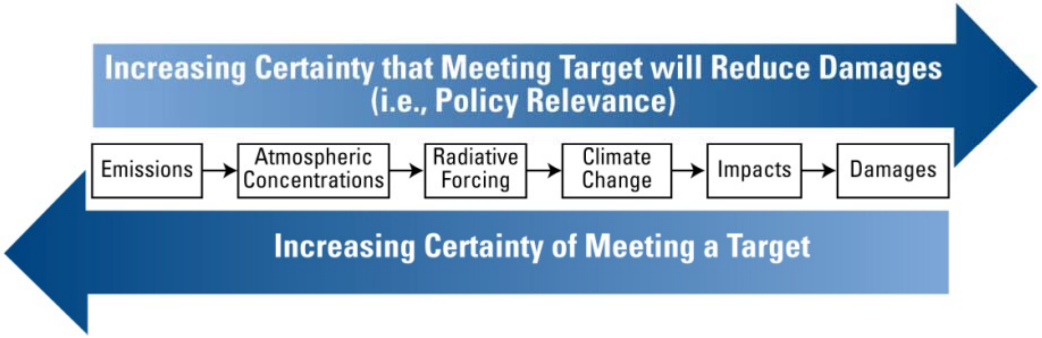


Potential Benefits of BC Mitigation

- Reducing current emissions of BC may help slow the near-term rate of climate change, particularly in sensitive regions such as the Arctic.
- 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.
- Due to the differences between BC and long-lived GHGs like carbon dioxide (CO_2), it is very difficult to compare them using standardized metrics. Reductions in BC and GHGs are complementary strategies for mitigating climate change.
- The health and environmental benefits of BC reductions are also substantial.
  - Average public health benefits of reducing directly emitted $PM_{2.5}$ in the U.S. are estimated to range from \$290,000 to \$1.2 million per ton $PM_{2.5}$ in 2030.
  - At the global scale, the $PM_{2.5}$ reductions resulting from BC mitigation measures could potentially result in hundreds of thousands of avoided premature deaths each year.

Metrics for Comparing BC to CO_2

- There is currently no single metric that is widely accepted by the science and research community for the purpose of comparing BC and CO_2.
  - Metrics developed for CO_2, like global warming potential (GWP) and global temperature potential (GTP), are difficult to apply to BC due to important differences (e.g., atmospheric lifetime) between BC and long-lived GHGs.
  - New metrics designed specifically for short-lived climate forcers like BC have been developed, including the specific forcing pulse (SFP) and the surface temperature response per unit continuous emission (STRE).
- Choice of metric depends on the policy goal. Factors to consider in selecting a metric include:
  - the time scale (e.g., 20 years, 100 years, or more)
  - the nature of the impact (radiative forcing, temperature, or other damages)
  - the inclusion of different processes (indirect effects, snow/ice albedo changes, co-emissions)
  - whether impacts of concern are regional or global
- If goal is reducing <u>long-term change</u>, then a metric like a 100-year GWP or GTP is most appropriate.
- If goal is also to reduce the <u>rate of change</u> and <u>near-term damages to sensitive regions</u>, no single existing metric adequately weights impacts over both time periods, and a multi-metric approach may be preferred.



Mitigating BC: Key Considerations

- Targeted strategies to reduce BC emissions can be expected to provide near-term climate, health and environmental benefits.
- It is important to consider the location and timing of emissions and to account for co-emissions.
  - BC is emitted with other particles and gases (such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), organic carbon (OC) and CO_2), many of which exert a cooling influence on climate. This needs to be considered in selecting mitigation strategies. Reductions in emissions from BC-rich sources (e.g., mobile diesels) have the greatest likelihood of providing climate benefits.
  - 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.
  - Health benefits depend on how emissions reductions affect human exposure, in terms of both improvements in air quality and the size of the affected population.
- Control technologies are available to reduce BC emissions from a number of source categories. These reductions are generally achieved by improving combustion and/or controlling 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.

POTENTIAL BENEFITS = MITIGATION POTENTIAL +/- CONSTRAINING FACTORS

Goals

Climate
Radiative Forcing
Temperature
Ice/Snow Melt
Precipitation

Health
Ambient Exposures
Indoor Exposures

Environment
Surface Dimming
Visibility

Emissions sources

Stationary Sources
Brick Kilns
Coke Ovens
Diesel Generators
Utilities
Flaring

Open Biomass Burning
Agricultural Burning
Prescribed Burning
Wildfire

Mobile Sources
On-Road Diesel
On-Road Gasoline
Construction Equip.
Agricultural Equip.
Locomotives
Marine

Residential Cooking and Heating
Cookstoves
Woodstoves
Hydronic Heaters

Mitigation options

Available Control Technologies
e.g. Diesel Particulate Filters

Alternative Strategies to Reduce Emissions
e.g. Efficiency Improvements, Substitution

Constraining factors

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

BC Mitigation Opportunities

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 U.S. source categories have more limited mitigation potential due to smaller remaining emissions in these categories, or limits on the availability of effective BC control strategies. These include:
  - stationary sources (industrial, commercial and institutional boilers, stationary diesel engines, uncontrolled coal-fired EGUs)
  - residential wood combustion (hydronic heaters and woodstoves)
  - open biomass burning

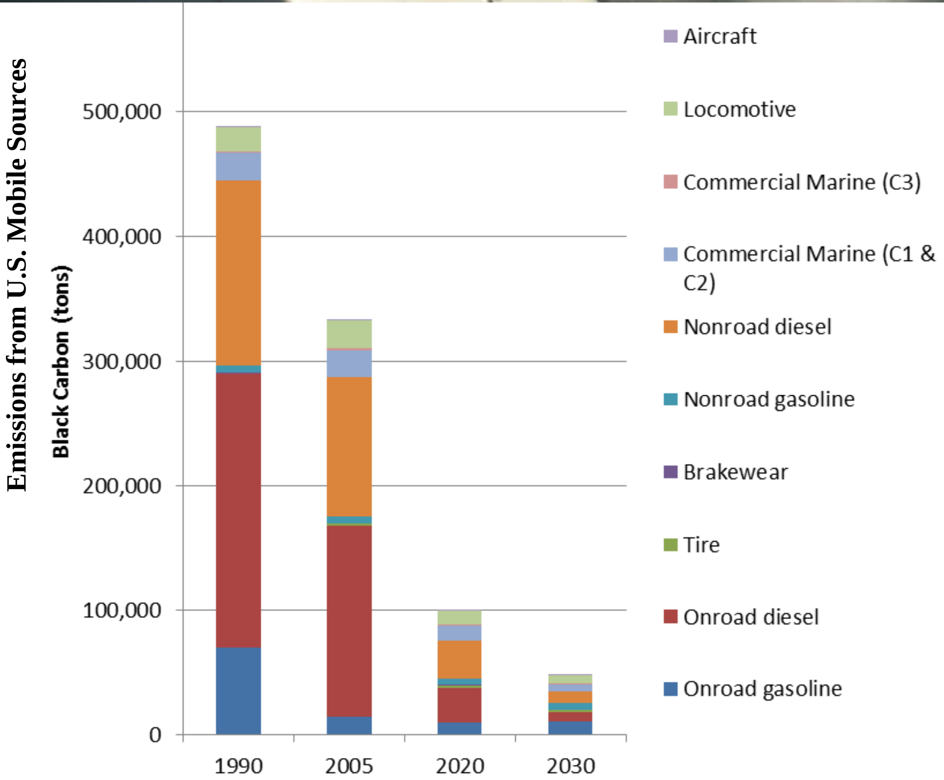
Global

- The most important BC emissions reduction opportunities globally include:
  - residential cookstoves in all regions
  - brick kilns and coke ovens in Asia
  - 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 number of mobile sources increasing rapidly.

Sensitive Regions

- Arctic: transportation sector (land-based diesel engines and Arctic shipping); residential heating (wood-fired stoves and boilers); and forest, grassland and agricultural burning.
- Himalayas: residential cooking; industrial sources (especially coal-fired brick kilns); and transportation, primarily on-road and off-road diesel engines.

Mobile Sources



United States

- BC emissions from mobile diesel engines (including on-road, non road, locomotive, and commercial marine engines) controlled via:
  - Emissions standards for new engines, including requirements resulting in use of diesel particulate filters (DPFs) in conjunction with ultra low sulfur diesel fuel.
  - Retrofit programs for in-use mobile diesel engines, such as EPA's National Clean Diesel Campaign and the SmartWay Transport Partnership Program.
- Total U.S. mobile source BC emissions are projected to decline by 86% by 2030 due to regulations already promulgated.
  - EPA has estimated the cost of controlling $PM_{2.5}$ from new diesel engines at ~ $14,000/ton (2010$).

Global

- New engine standards and retrofits can both help reduce BC emissions.
  - Many other countries have already begun phasing in emissions and fuel standards.
- Mobile source BC emissions in developing countries are expected to continue to increase. Emissions control requirements lag behind in some regions, as does deployment of diesel particulate filters (DPFs) and low sulfur fuels.
  - Reducing BC will depend on accelerated deployment of clean engines and fuels.

Stationary Sources

United States

- Controls on industrial sources, combined with improvements in technology and broader deployment of cleaner fuels such as natural gas, have helped reduce U.S. BC emissions more than 70% since the early 1900s.
- Regulations limiting direct PM emissions (including BC) affect more than 40 categories of industrial sources, including coke ovens, cement plants, industrial boilers, and stationary diesel engines.
- Available control technologies and strategies include:
  - Use of cleaner fuels.
  - Direct $PM_{2.5}$ reduction technologies (e.g. fabric filters (baghouses), electrostatic precipitators (ESPs), and diesel particulate filters (DPFs)).
  - The control technologies range in cost-effectiveness from $48/ton $PM_{2.5}$ to $685/ton $PM_{2.5}$ (2010$) or more, depending on the source category. However, they also may involve tens of millions in initial capital costs.

Global

- The largest stationary sources of BC emissions internationally include:
  - Brick kilns
  - Coke ovens (largely from iron/steel production)
  - Industrial boilers
- Replacement or retrofit options already exist for many sources.
  - Reducing emissions from smaller, inefficient facilities may require phasing out or replacing the entire unit
  - Larger facilities can apply many of the existing PM filter technologies already in commercial use.

Brick Kiln in Kabul

Residential Heating and Cooking

United States

- Emissions from residential wood combustion 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 replacing or retrofitting existing units, or switching to alternative fuels such as natural gas.
  - New EPA-certified wood stoves have a cost-effectiveness of about \$3,600/ton $PM_{2.5}$ reduced, while gas fireplace inserts average \$1,800/ton $PM_{2.5}$ reduced (2010\$).

Global

- Residential wood combustion is also a significant source of BC emissions in the Arctic.
  - The Arctic Council Task Force on Short-Lived Climate Forcers has identified wood stoves and boilers as a key mitigation opportunity for Arctic nations, pointing to measures such as emissions standards, change-out programs, and retrofits to reduce BC from wood stoves, boilers, and fireplaces.
- Emissions from traditional cookstoves are both a large source of BC and a major threat to public health in developing countries.
  - Approximately 3 billion people worldwide cook their food or heat their homes by burning biomass or coal in rudimentary stoves or open fires.
- Reducing these emissions 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. This is the goal of the Global Alliance of Clean Cookstoves launched in 2010.
  - A wide range of improved stove technologies is available, but the potential climate and health benefits vary substantially by technology and fuel.

Open Biomass Burning

- Open biomass burning is the largest source of BC emissions globally, and these emissions have been tied to reduced snow and ice albedo in the Arctic.
  - Open biomass burning emissions are greatest in Africa, Asia, and South America; emissions in Russia/Central Asia and North America also significant.
  - A large percentage of these emissions are due to wildfire, and total OC emissions are seven times higher than total BC emissions from this sector.
  - More data are needed on BC emissions from fires and their climate impacts.
- $PM_{2.5}$ emissions reductions techniques (e.g., smoke management programs) may help reduce BC emissions.
- Appropriate mitigation measures depend on the timing and location of burning, resource management objectives, vegetation type, and available resources.
  - Fire plays an important ecological role in many ecosystems, and prescribed burning is one of the basic tools utilized to achieve multiple land-management objectives in fire-dependent ecosystems.
  - 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.
- Expanded wildfire prevention efforts may help to reduce BC emissions worldwide.

Research Needs

Key uncertainties:

- Atmospheric processes affecting BC concentrations (e.g., transport and deposition)
- Aerosol-cloud interactions (e.g., radiative and precipitation effects)
- Climate effects of aerosol mixing state
- Emissions of BC and co-emitted pollutants from specific regions, sources
- Warming effect of non-BC aerosols in Arctic
- Impacts of BC on snow and ice albedo
- Climate impacts of other types of light-absorbing carbonaceous particles (e.g., “Brown Carbon”)
- Shape and magnitude of PM health impact function
- Differential toxicity of PM components and mixtures
- Impacts of BC on ecosystems and crops (dimming)

Policy-relevant research needs:

- Continued investigation of basic microphysical and atmospheric processes affecting BC and other aerosol species to support the development of improved estimates of radiative impacts, particularly indirect effects.
- Improving global, regional, and domestic BC emissions inventories with more laboratory and field data on activity levels, operating conditions, and technological configurations, coupled with better estimation techniques for current and future emissions.
- Focused investigations of the climate impacts of brown carbon (BrC).
- Research on the impact of aerosols in snow- and ice-covered regions such as the Arctic.
- Standardized definitions and improved instrumentation and measurement techniques for light-absorbing PM, coupled with expanded observations.
- Continued investigation of the differential toxicity of PM components and mixtures and the shape and magnitude of the PM health impact function.
- More detailed analysis and comparison of the costs and benefits of mitigating BC from specific types of sources in specific locations.
- Refinement of policy-driven metrics relevant for BC and other short-lived climate forcers.
- Analysis of key uncertainties.

Conclusions

- Mitigation of BC offers a clear opportunity: continued reductions in BC emissions can provide significant near-term benefits for climate, public health, and the environment.

- Effective control technologies and approaches are available to reduce BC emissions from a number of key source categories.
  - These approaches could be utilized to achieve further BC reductions in the United States and globally.
  - BC mitigation solutions vary significantly by region, and must be adapted based on the specific needs and implementation challenges faced by individual countries.

- 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 are mainly due to control programs aimed at $PM_{2.5}$ (especially secondarily formed $PM_{2.5}$), not targeted efforts to reduce BC per se.
  - Greater attention to BC-focused strategies has the potential to help protect the climate while ensuring continued improvements in public health.

- The options identified in this report for reducing BC emissions are consistent with control opportunities emphasized in other recent assessments. These represent important mitigation opportunities for key world regions, including the United States.