Black Carbon

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Bay Area AQMD Advisory Council
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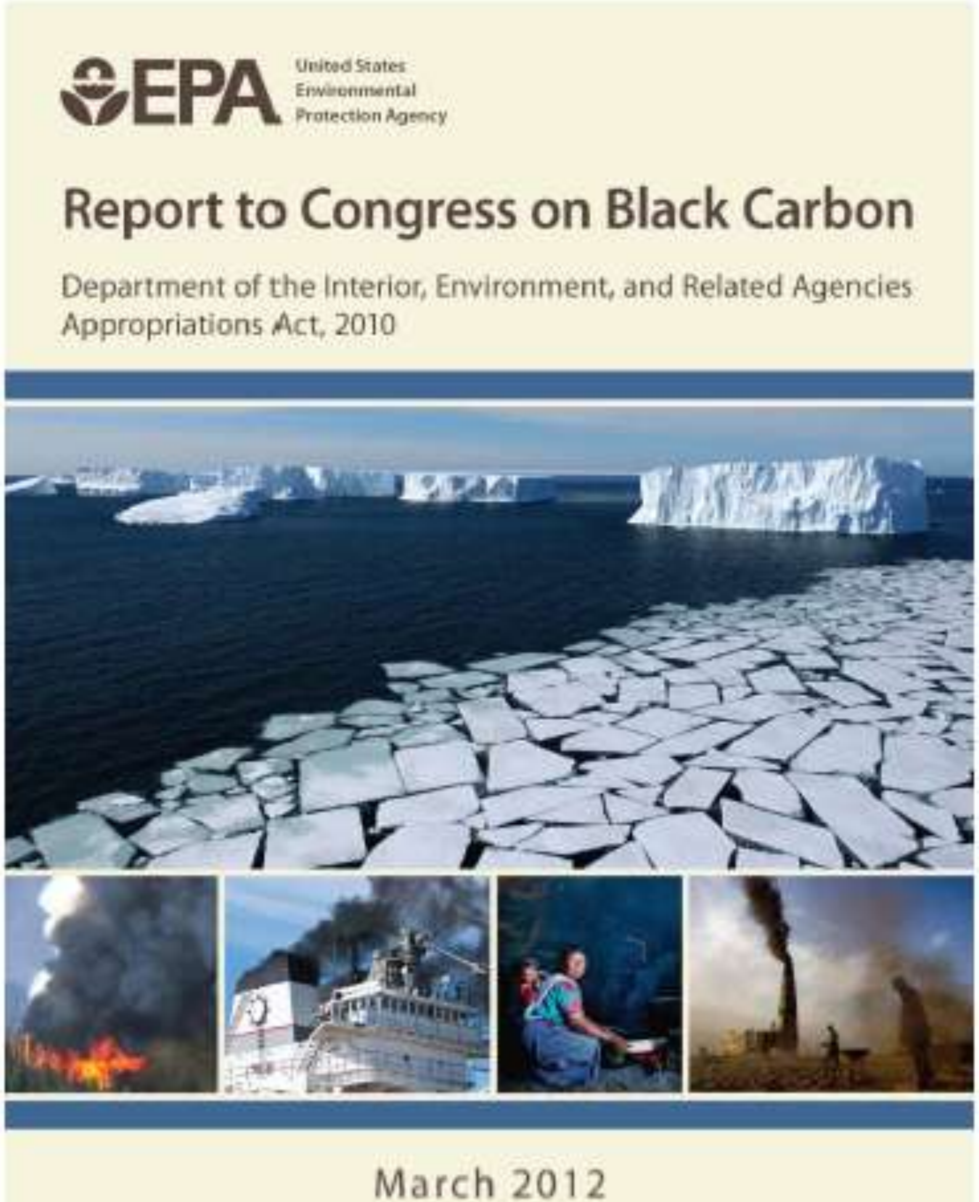
Outline

- ➢ Basics & Definition
- ➢ Inventories and trends
- ➢ Climate forcing
- ➢ Co-pollutants
- ➢ Metrics
- ➢ Mitigation
- ➢ EPA work on Black Carbon (BC)

Sources: EPA Report to Congress, recent Bounding Study (Bond et al. 2013)

Black Carbon Basics & Definition

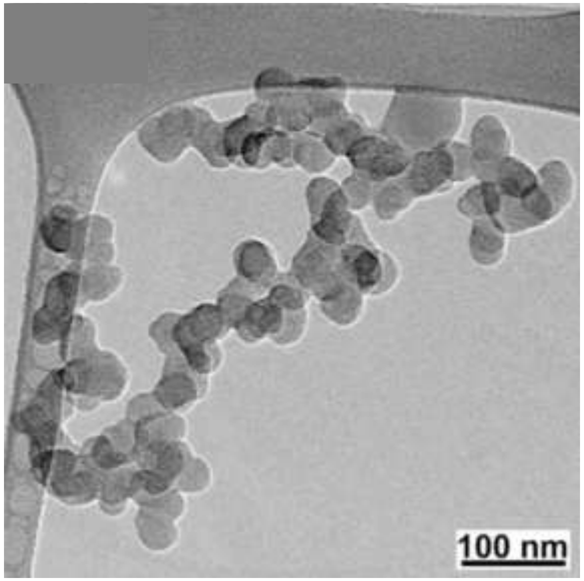


The Report:

- 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.

www. epa.gov/blackcarbon

What is Black Carbon?

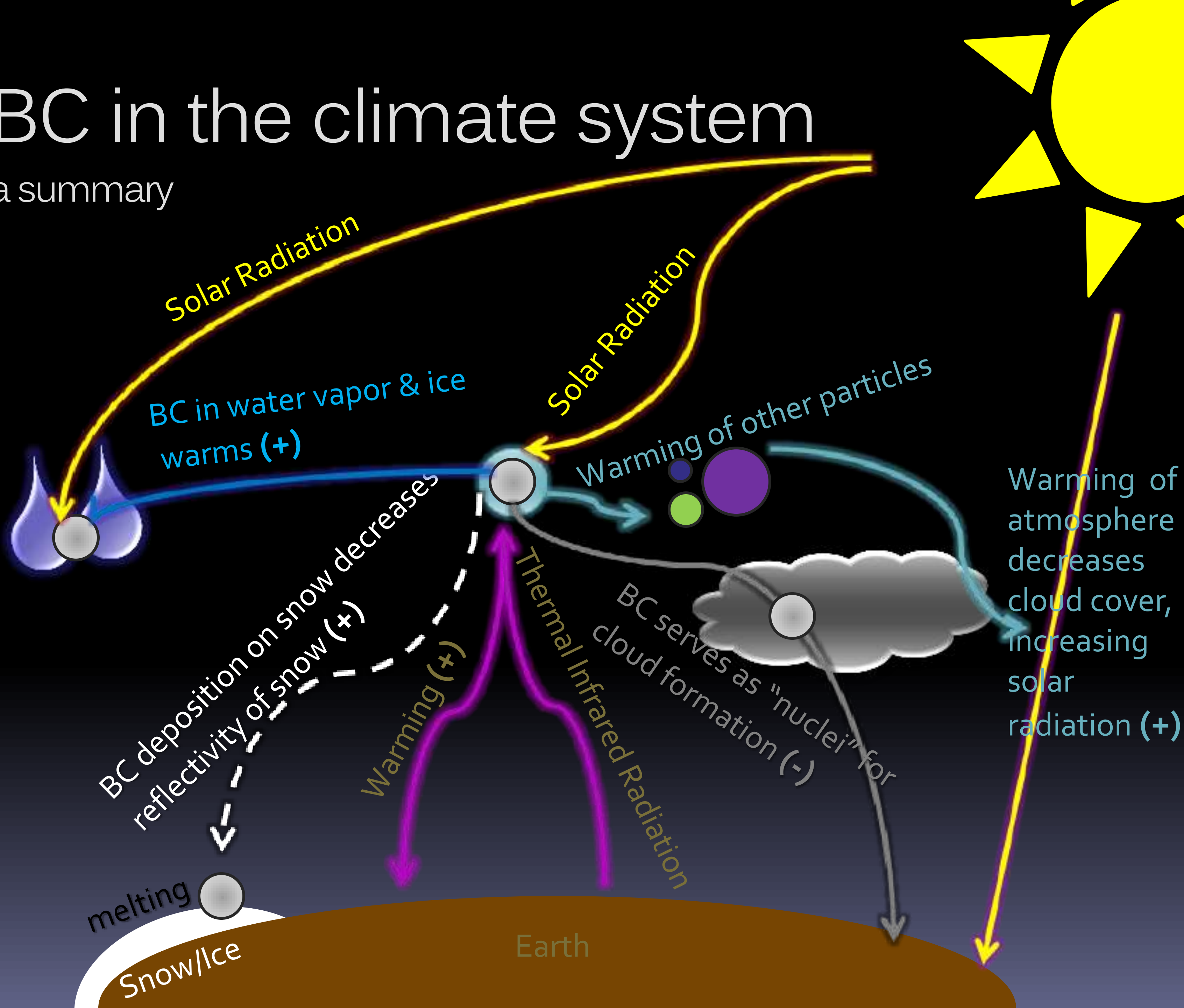


- Black carbon is the most strongly light-absorbing component of particulate matter (PM).
  - BC is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths.
- BC is formed by incomplete combustion of fossil fuels, biofuels, and biomass.

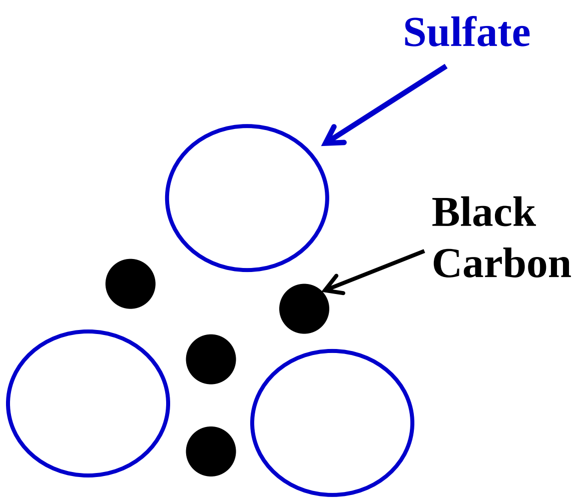
- Aggregate of small spheres
- Insoluable in water and organic solvents
- Short atmospheric lifetime

BC in the climate system

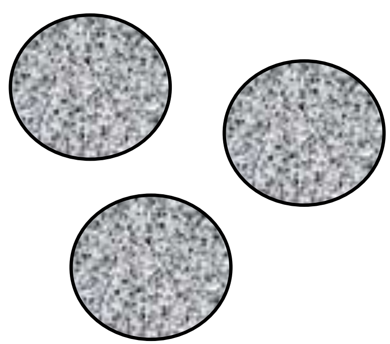
a summary



Mixing State of Black Carbon



External Mixture



Internal Mixture

- Freshly emitted BC particles are externally mixed, whereas aged BC particles are mostly mixed internally
- Internal mixing of BC alters its aggregate shape, hygroscopic, and optical properties
- Knowledge of mixing state of BC containing particles is important for
  - Calculating their radiative forcing
  - Providing insight into their source and life cycle

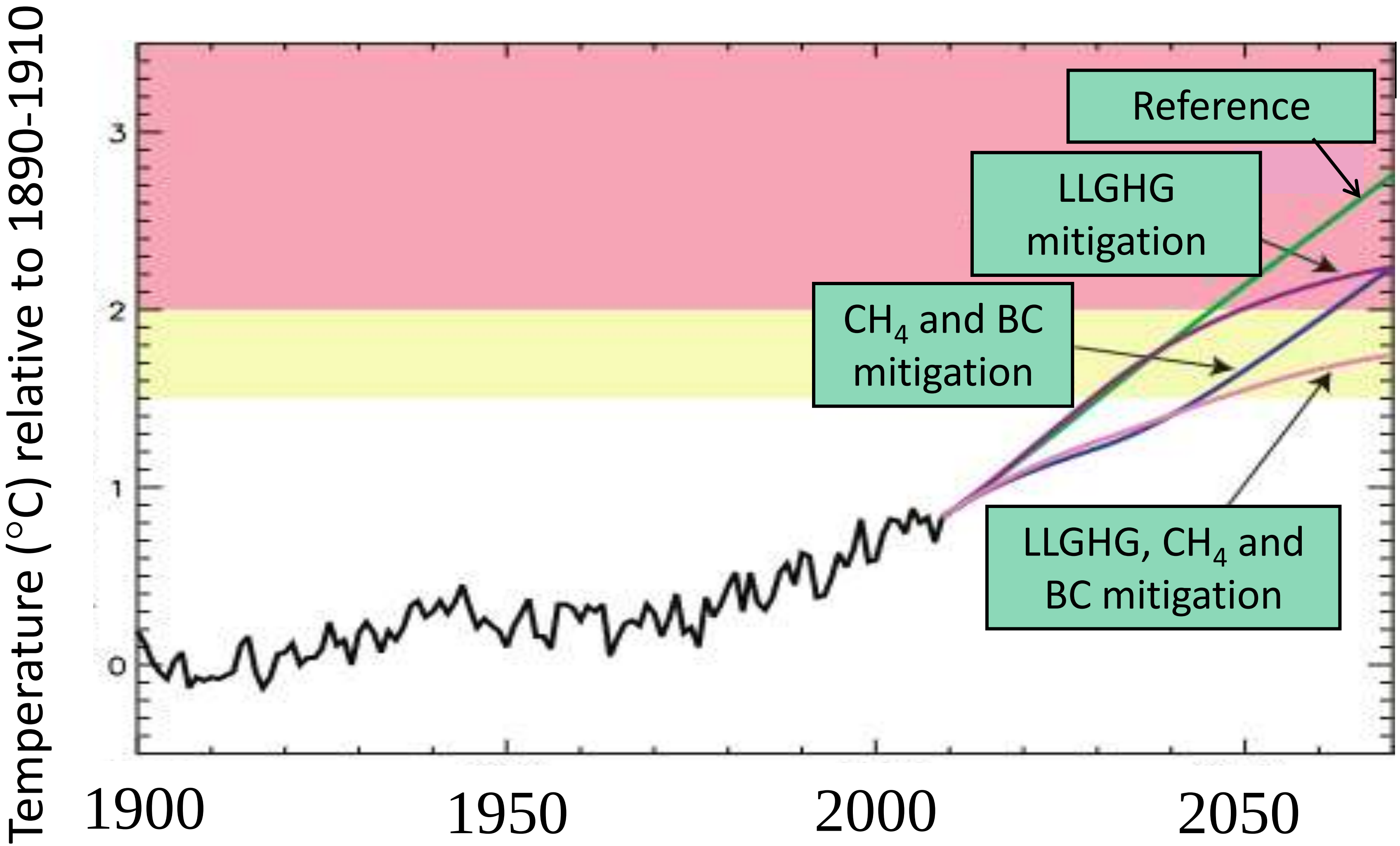
Health Effects of Black Carbon

- Health effects associated with BC are consistent with those associated with $PM_{2.5}$.
  - Includes respiratory and cardiovascular effects and premature death.
- Emissions and ambient concentrations of directly emitted $PM_{2.5}$ are often highest in urban areas, where large numbers of people live.
- 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.
- Globally, BC mitigation measures could potentially lead to hundreds of thousands of avoided premature deaths each year.

Brick Kiln in Kathmandu

EPA Report to Congress

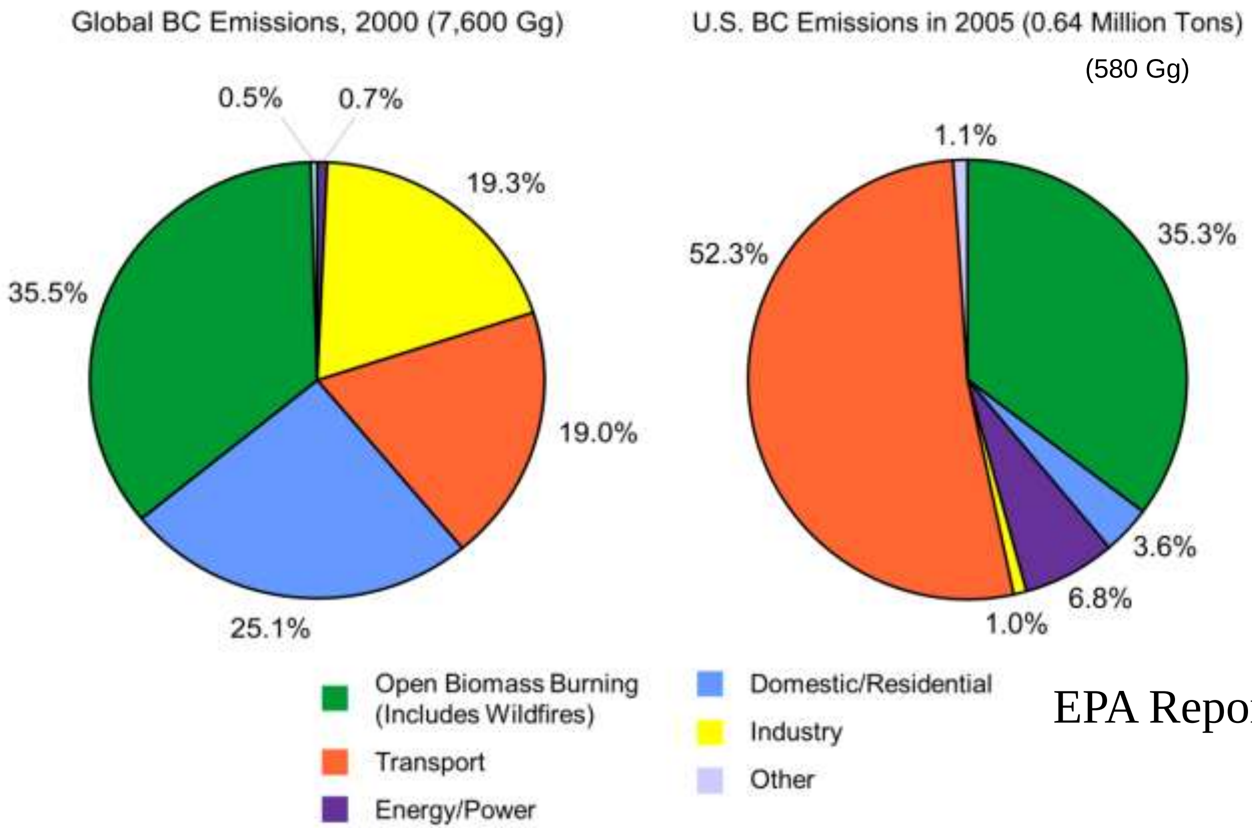
Near-term climate benefits



UNEP/WMO Integrated Assessment of BC and Ozone, 2011; Shindell et al. *Science*, 2012

Black Carbon Inventories & Trends

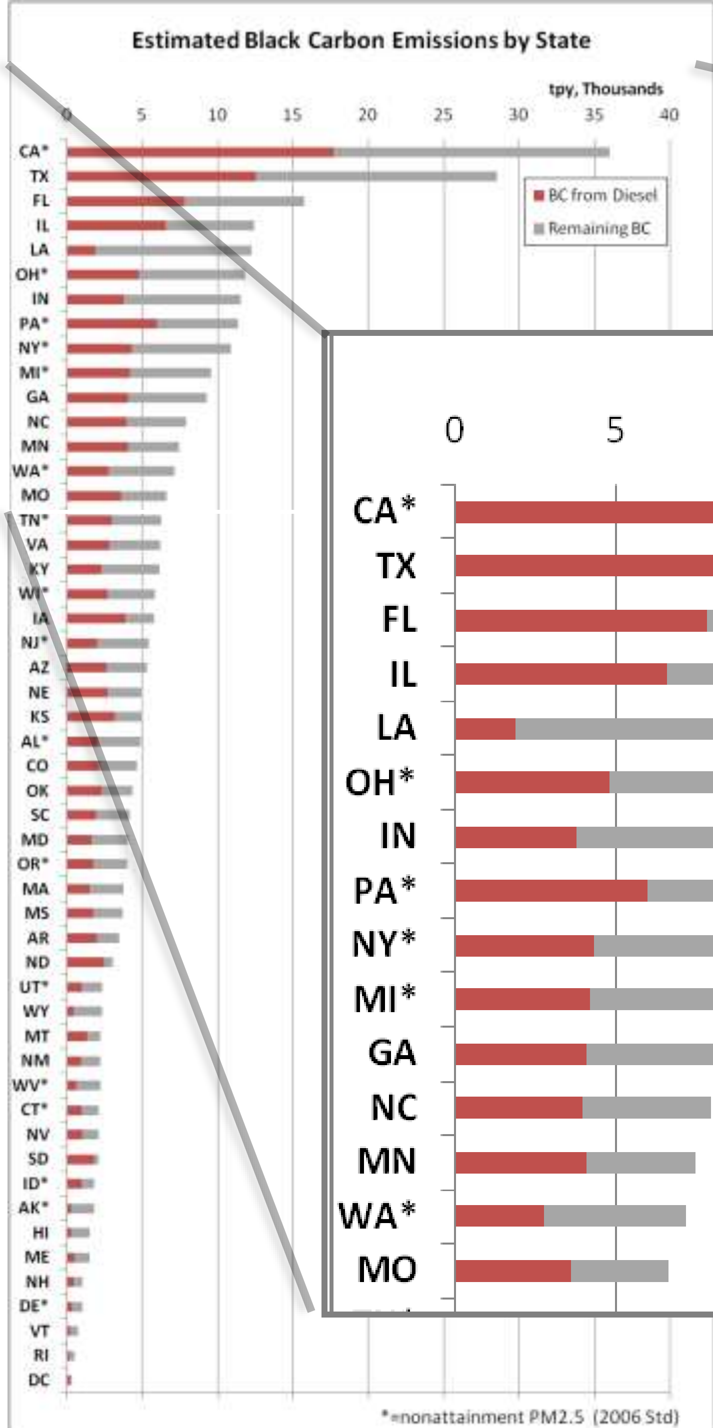
Black Carbon Emissions

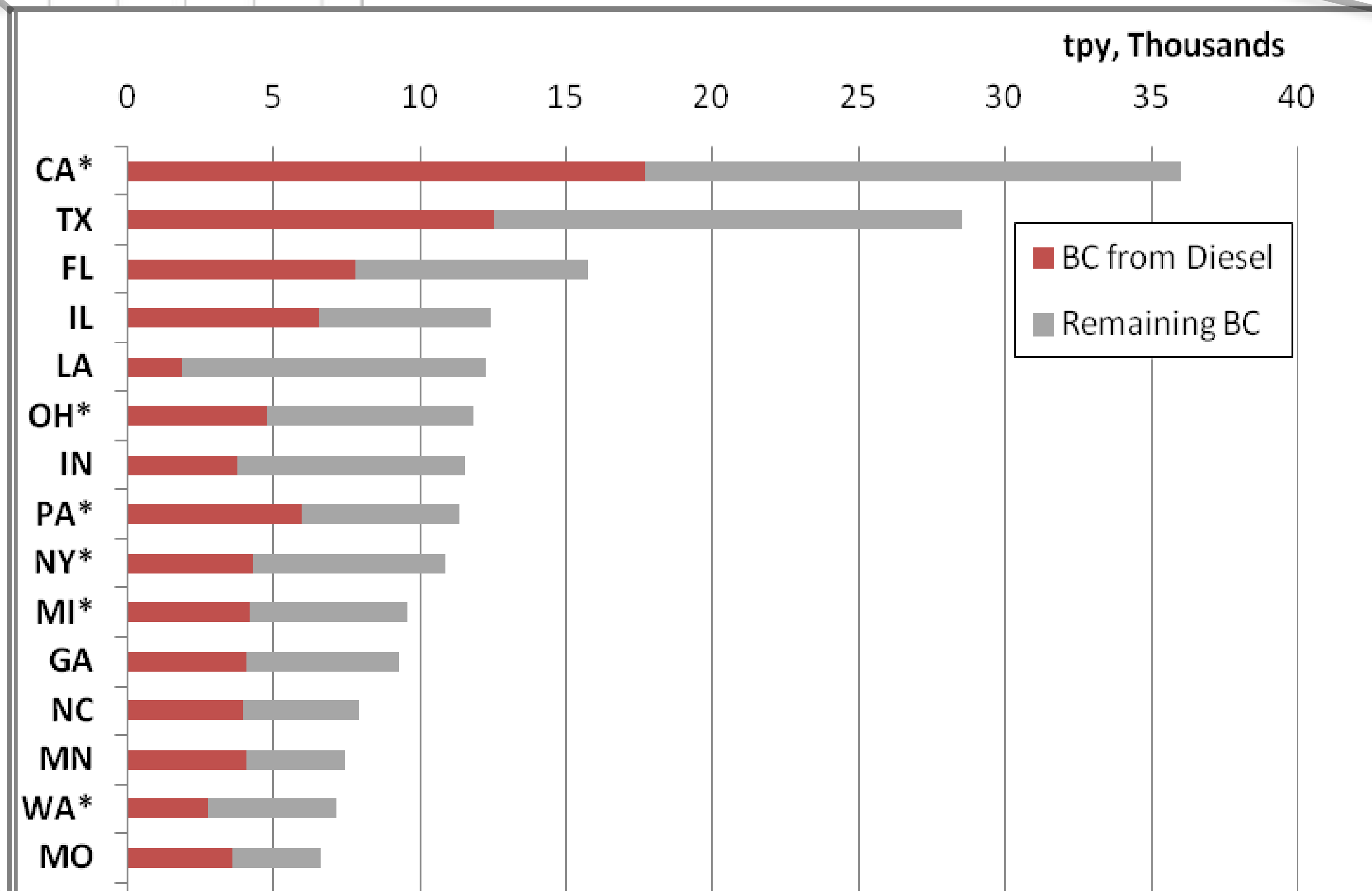


EPA Report to Congress

- 75% of global BC emissions come from Asia, Africa and Latin America.
- U.S. 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.
- In the U.S., BC emissions ~12% of all direct $PM_{2.5}$ emissions nationwide.
- Mobile sources are the largest U.S. BC emissions category (with 93% of mobile source BC coming from diesels).

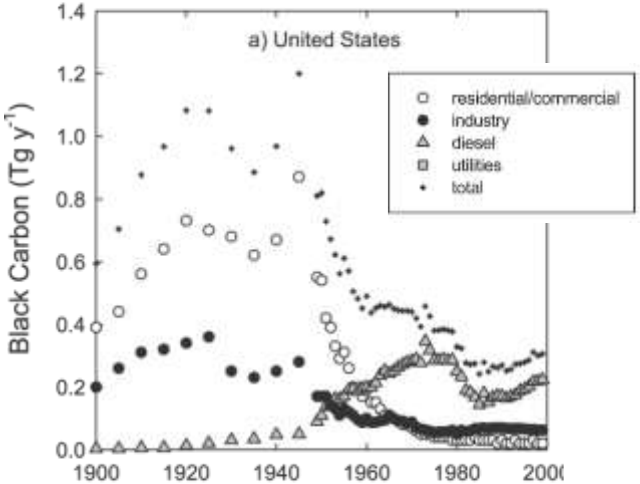
State Inventories for Black Carbon

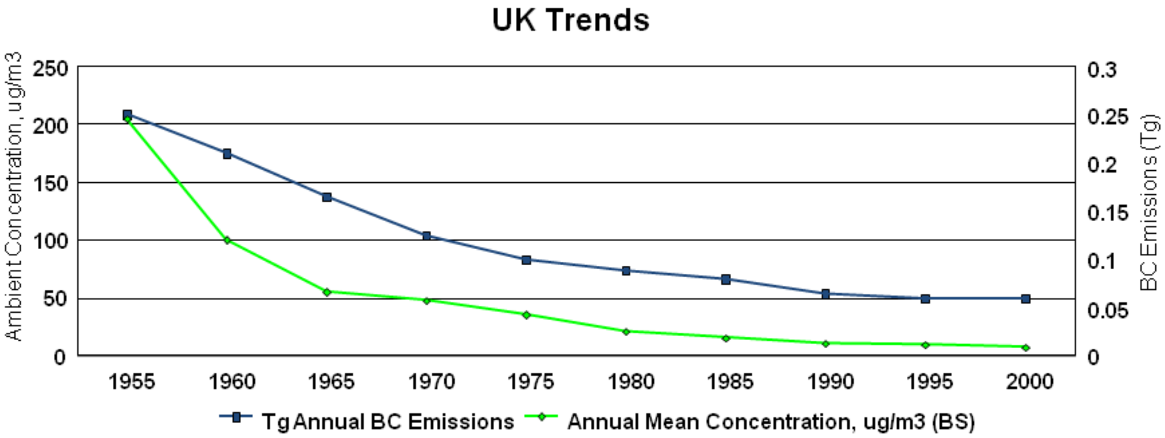




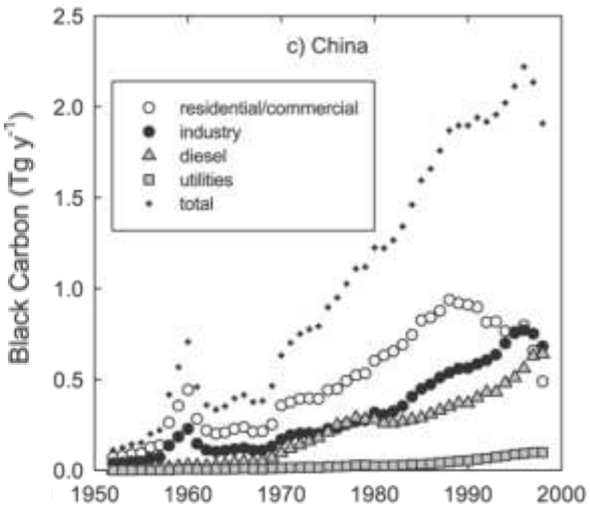
Black Carbon Emissions: Global Trends

- 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.





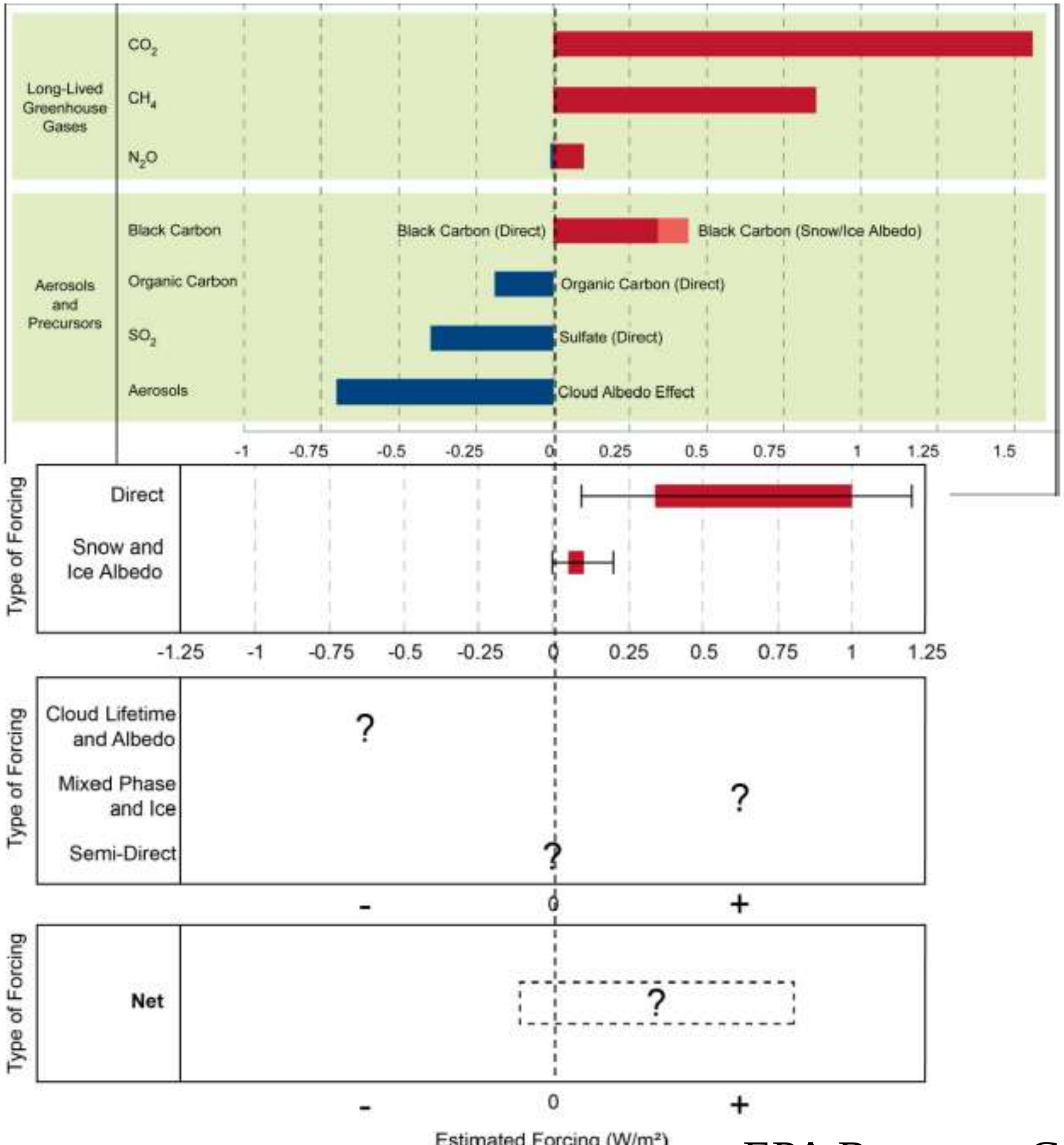
- Developing countries (e.g., China and India) have shown a very sharp rise in BC emissions over the past 50 years.
- Total global BC emissions are likely to decrease in the future, but developing countries may experience emissions growth in key sectors (transportation, residential).



EPA Report to Congress

Black Carbon Climate Forcing

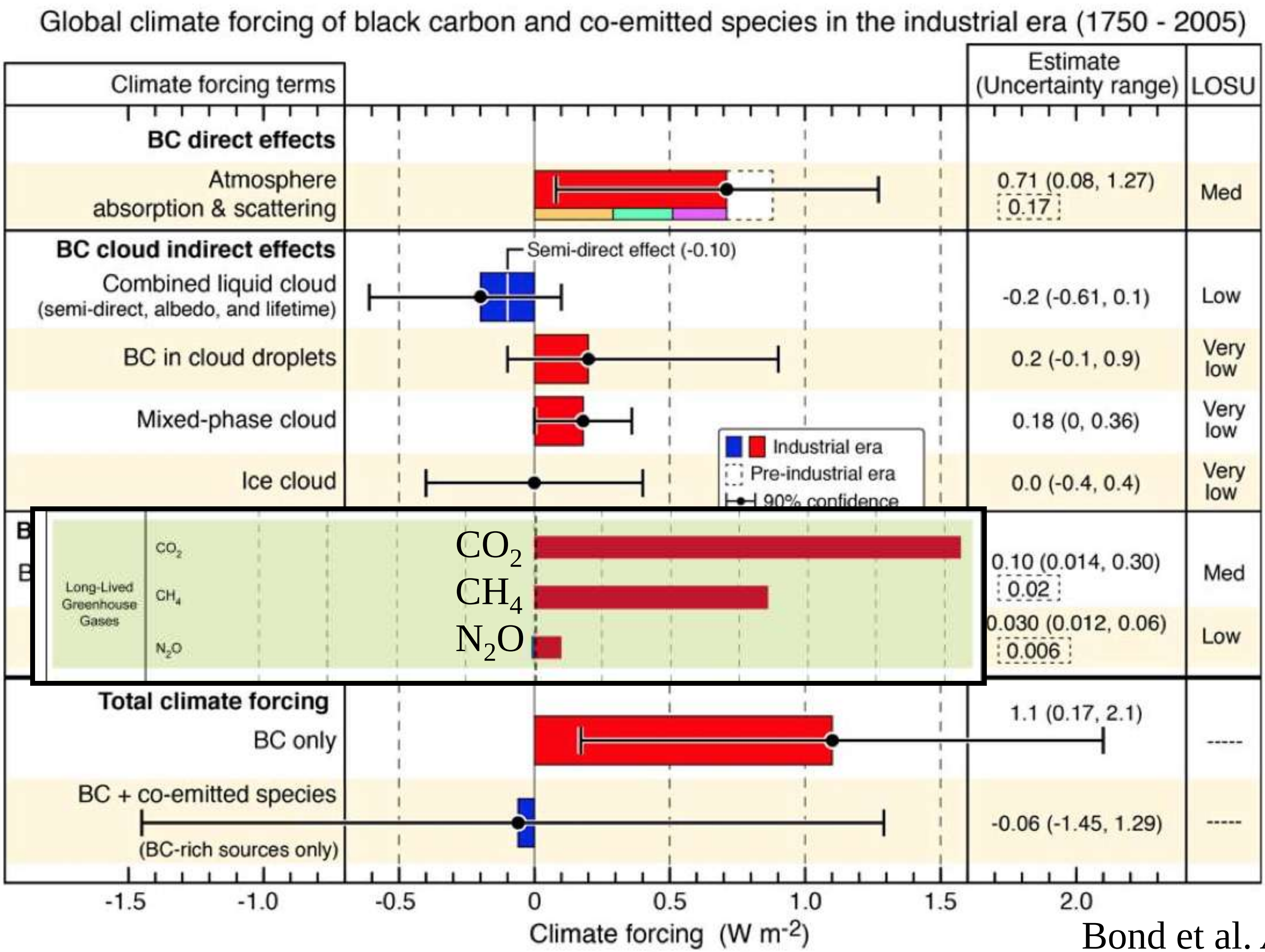
EPA Report to Congress: Total BC forcing uncertain



- IPCC (2007) used an estimate of 0.34 Wm^{-2} for direct BC RF, and estimated an additional 0.1 Wm^{-2} RF for snow and ice deposition.
- The IPCC estimate does not account for indirect and semi-direct cloud forcing.
- Recent studies have suggested greater possible warming for the direct effect.
- Several recent studies have suggested a lower RF for snow and ice effects.
- Total BC RF is still dominated by uncertainty about potentially significant indirect effects on clouds.

EPA Report to Congress

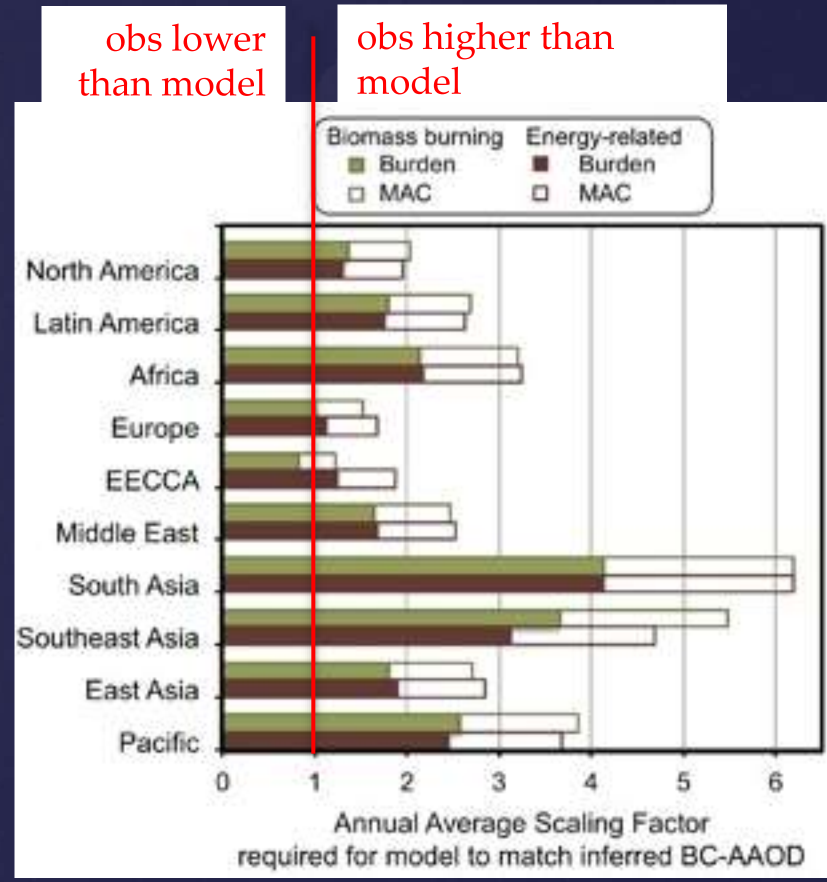
Bounding Study: BC Forcing is net warming; best estimate is that it's second only to CO_2



Bond et al. *AGU* 2013

Direct forcing

- Most estimates of direct forcing have been too low
  - Bounding-BC: +0.71 W/m2
  - IPCC AR4: +0.34 W/m2
- There is more absorption in the real atmosphere than in the simulations
  - More in line with previous *Ramanathan & Carmichael*
  - Causes are evaluated and attributed to regions
- Large uncertainties
  - (+0.08 to +1.27 W/m^2 – 90% confidence)

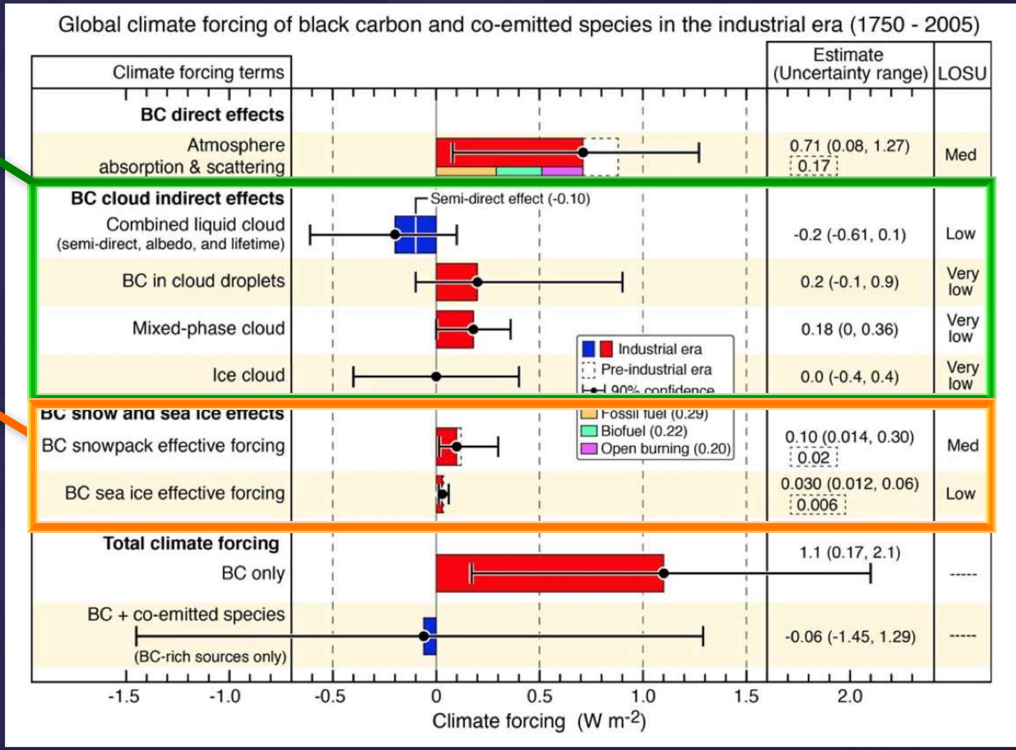


unshaded part of bar may be caused by "internal mixing"

Bond et al. *AGU* 2013

Total forcing

- Best estimate of total forcing +1.1 W/m^2
  - More warming than BC alone
- Cloud indirect: +0.18 W/m^2
  - Liquid clouds negative, but there are other effects
- Snow & sea ice: +0.13 W/m^2
- Very large uncertainties
  - Especially from clouds
  - Few models of some types of clouds
  - Few observational constraints
- <u>Despite uncertainties, BC is net warming</u>

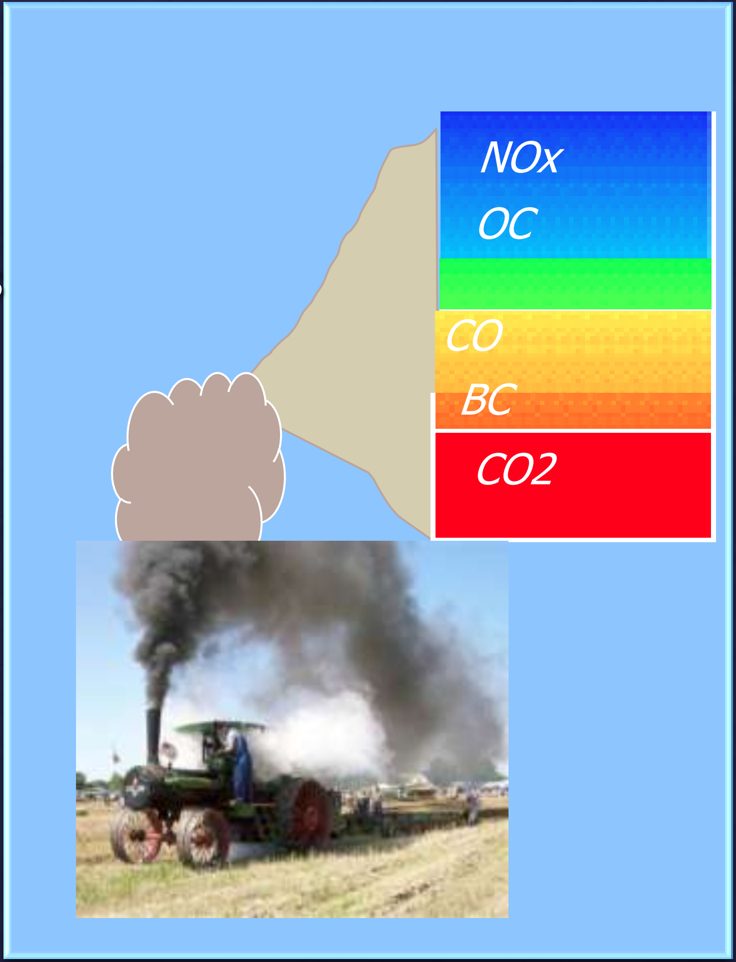


Bond et al. *AGU* 2013

Accounting for Co-pollutants

Co-emitted species

- Sources that emit black carbon also emit other short-lived species that affect climate
  - Sulfate: COOLING
  - Organic carbon: COOLING
  - Gases: WARMING or COOLING
- Shutting off a source entirely removes all species

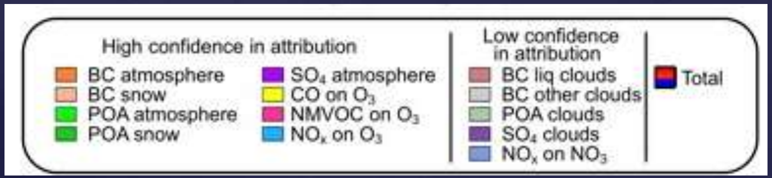


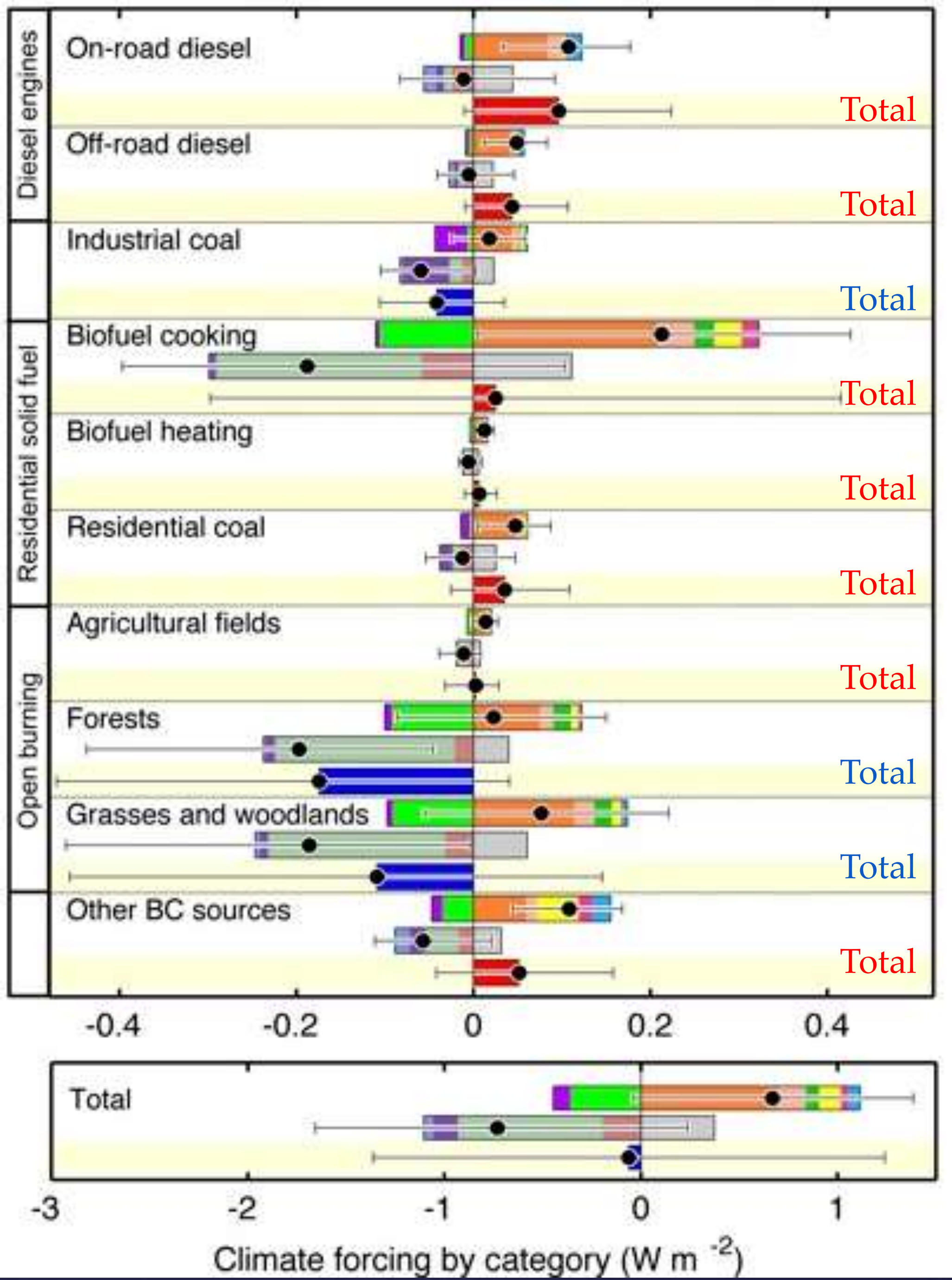
Bond et al. *AGU* 2013

Analysis for BC-rich source categories

Short-lived species only

- Some categories are net positive (red)
- Some are net negative (blue)
- Some are uncertain–sign unknown

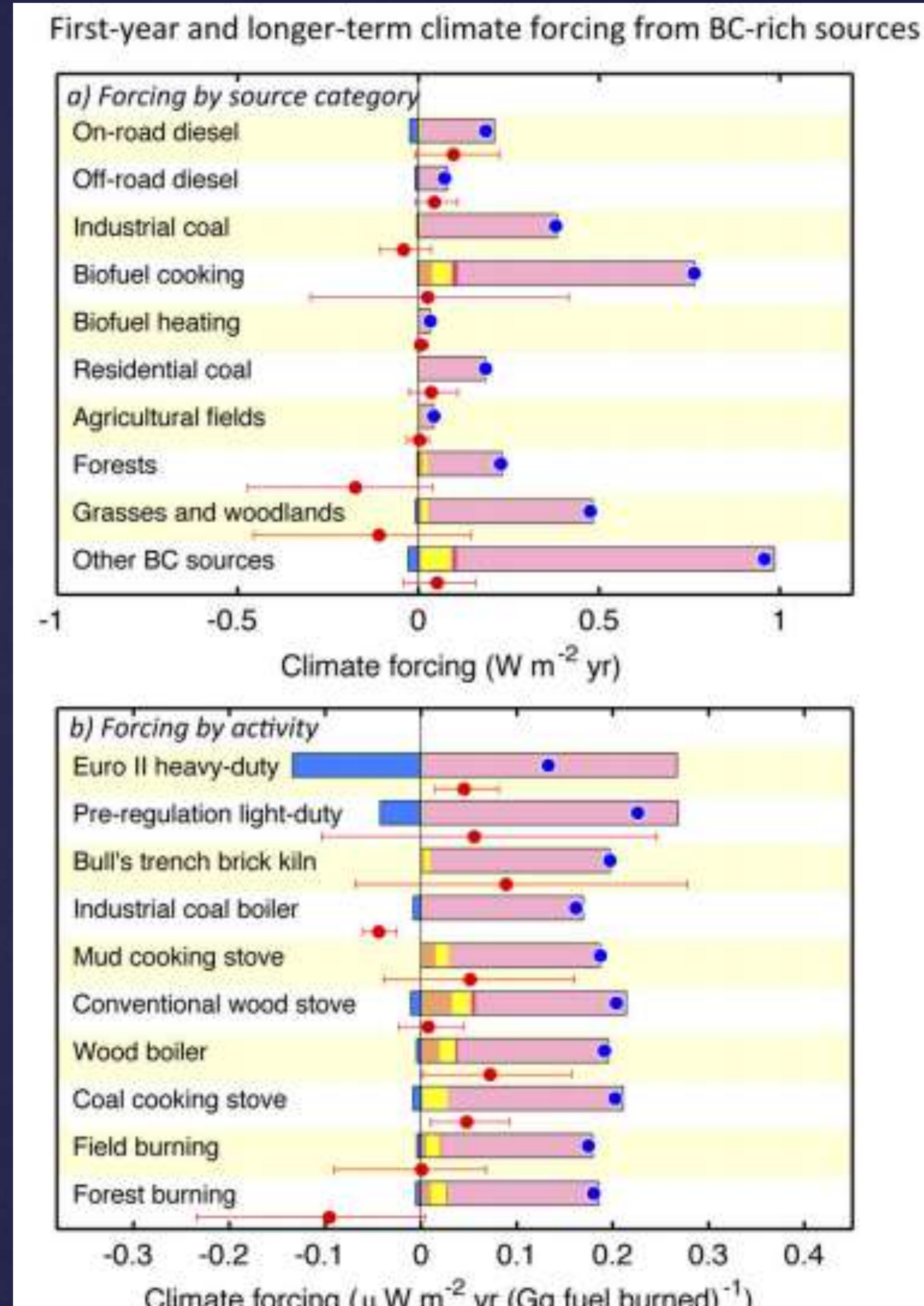


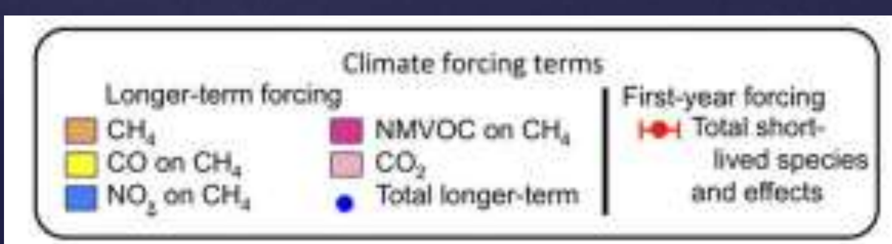


Bond et al. *AGU* 2013

Long-lived & Short-lived Climate forcers

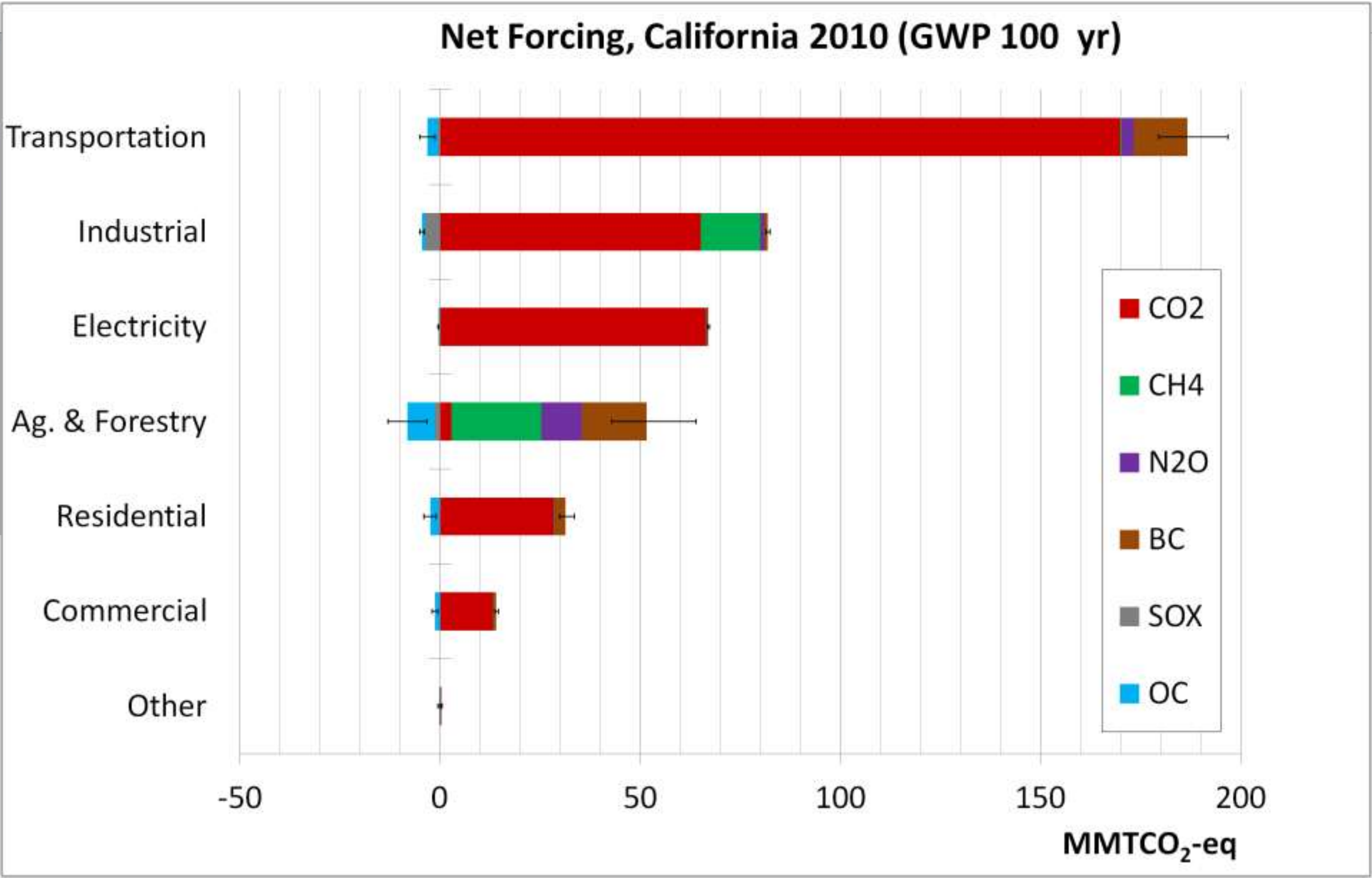
- Short-lived forcing (red)
- Long-lived forcing (blue)
- Sometimes additive, sometimes negate each other





Bond et al. *AGU* 2013

My own preliminary analysis in California



Black Carbon Climate Metrics

Black Carbon Climate Metrics

- Different types of climate equivalency metrics place value on different attributes

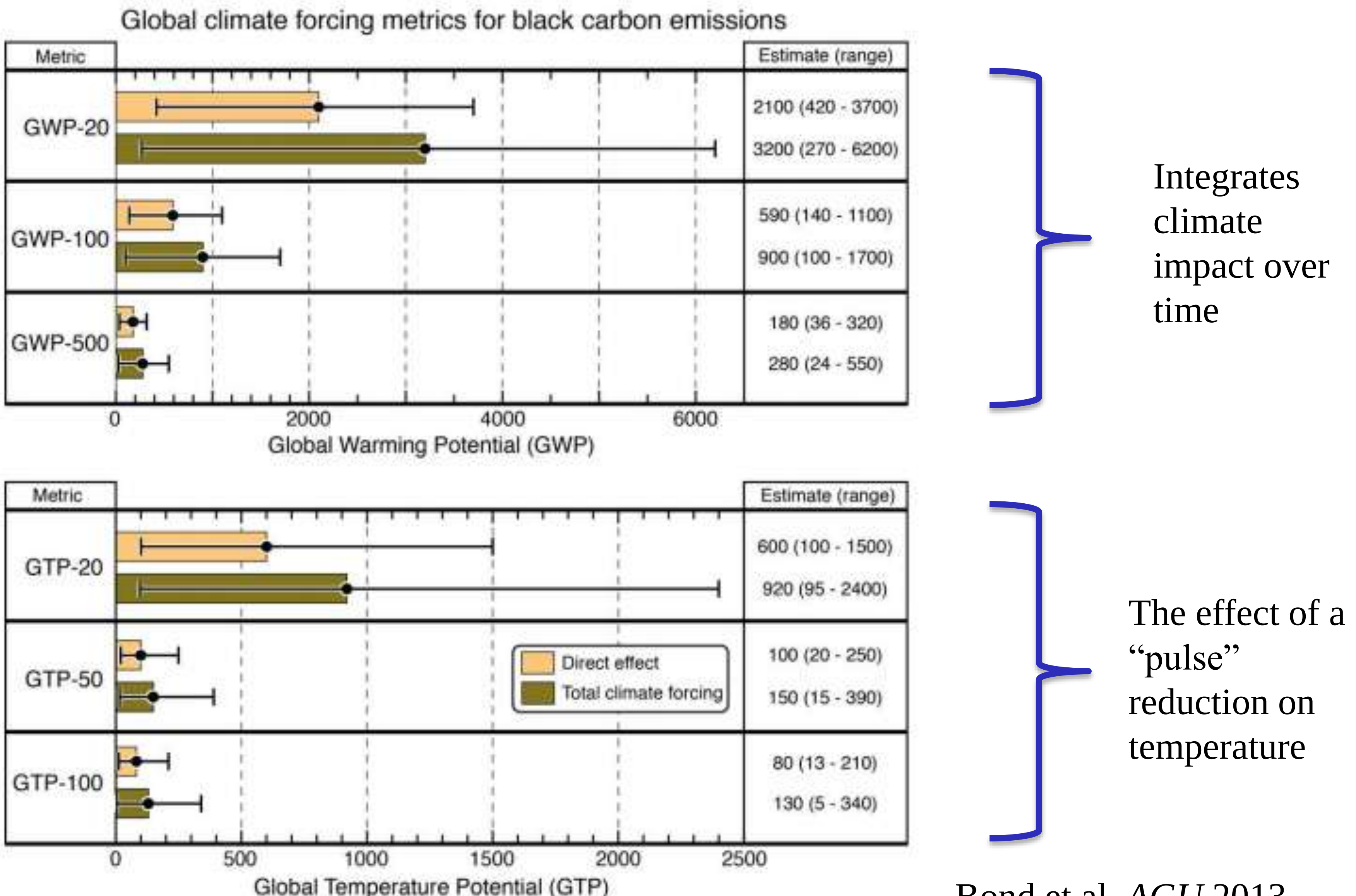
Table 2-8. Examples of Commonly Used Metrics for GHGs.

Metric Type	Climate Impact	Baseline Forcer	Emissions Type	Spatial Scale	Includes Rate of Change?
GWP (Global Warming Potential)	Integrated radiative forcing	CO_2	Pulse	Global	No
GTP-pulse (Global Temperature Potential)	Temperature	CO_2	Pulse	Global	No
GTP-sustained	Temperature	CO_2	Sustained	Global	No
STRE (Surface Temperature Response per unit continuous Emission)	Temperature	CO_2	Sustained	Global	No
SFP (Specific Forcing Pulse)	Energy	Joules/gram	Pulse	Global or regional	No
Cost-effectiveness Metrics (e.g., Manne and Richels, 2001, Global Cost Potential)	Mainly temperature	CO_2 or $ value	Optimal emissions calculation	Global	Optional
Value of Damages (e.g., Social Cost of Carbon, Global Damage Potential)	Range of climate damages	$ value	Pulse	Global	Limited

EPA Report to Congress

- The choice of the time horizon is also an important one

Black Carbon Climate Metrics



Bond et al. *AGU* 2013

Considerations for choosing & applying a metric

1. **Look for win-wins**: What are the mitigation strategies that maximize reductions of both LLGHG and SLCF?

2. **Consider institutional priorities:** Determine whether the focus of the institution has a greater emphasis on LLGHGs (may want to use a lower bound equivalency value for BC) or on SLCFs (may use an upper bound equivalency value for BC). In most cases, organizations will want to evaluate options with a range of values.

More emphasis on LLGHGs		*More emphasis on SLCFs*
Reduce temperature the long term	⟷	Delay impacts in the near term and risk of tipping points
Decrease global impacts	⟷	Decrease local impacts
Maximize climate benefit	⟷	Maximize health benefit
Not willing to accept uncertainty in climate forcing	⟷	Willing to accept some remaining uncertainties in climate forcing

3. **Analyze the decision:** What's the level of investment in the program? For high investment programs, use a wider range of values . Use a sensitivity analysis to see whether the outcome changes with the full range of equivalency values used.

Black Carbon Mitigation Opportunities

Mitigating BC: Key Considerations

- For both climate and health, it is important to consider the location and timing of emissions and to account for co-emissions.

- Available control technologies can reduce BC, generally by improving combustion and/or controlling direct $PM_{2.5}$ emissions from sources.

- Some state and local areas in the U.S. have already identified control measures aimed at direct $PM_{2.5}$ as particularly effective strategies for meeting air quality goals.

- Though the costs 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.

U.S. Residential Heating and Cooking

- 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.

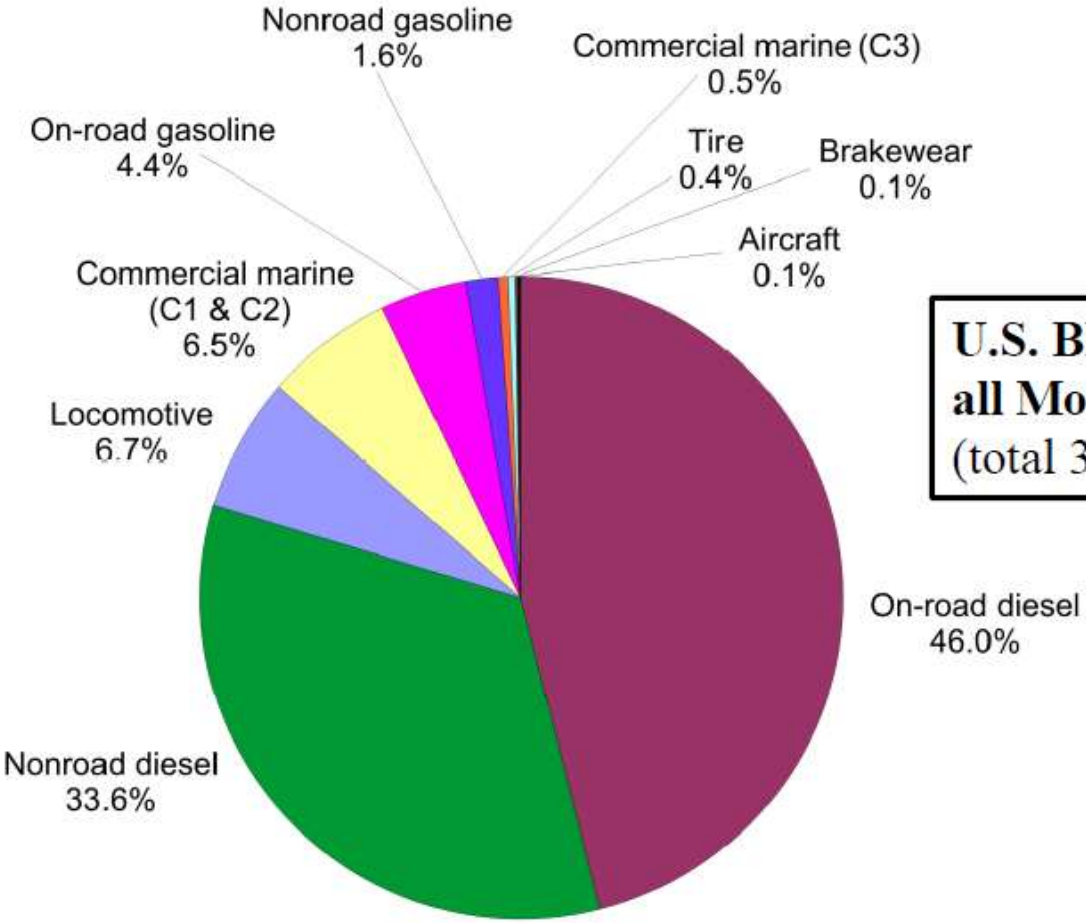
- Mitigation options include replacing or retrofitting existing units, or switching to alternative fuels such as natural gas.
  - New EPA-certified wood stoves have a cost-effectiveness of about \$3,600/ton $PM_{2.5}$ reduced, while gas fireplace inserts average \$1,800/ton $PM_{2.5}$ reduced (2010\$).

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.
  - A large percentage of these emissions are due to wildfire (e.g., U.S. Alaskan fires).
  - Total organic carbon (OC) emissions (which may be cooling) are seven times higher than total BC emissions from this sector.
- $PM_{2.5}$ 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.
- Expanded wildfire prevention efforts may help to reduce BC emissions worldwide.

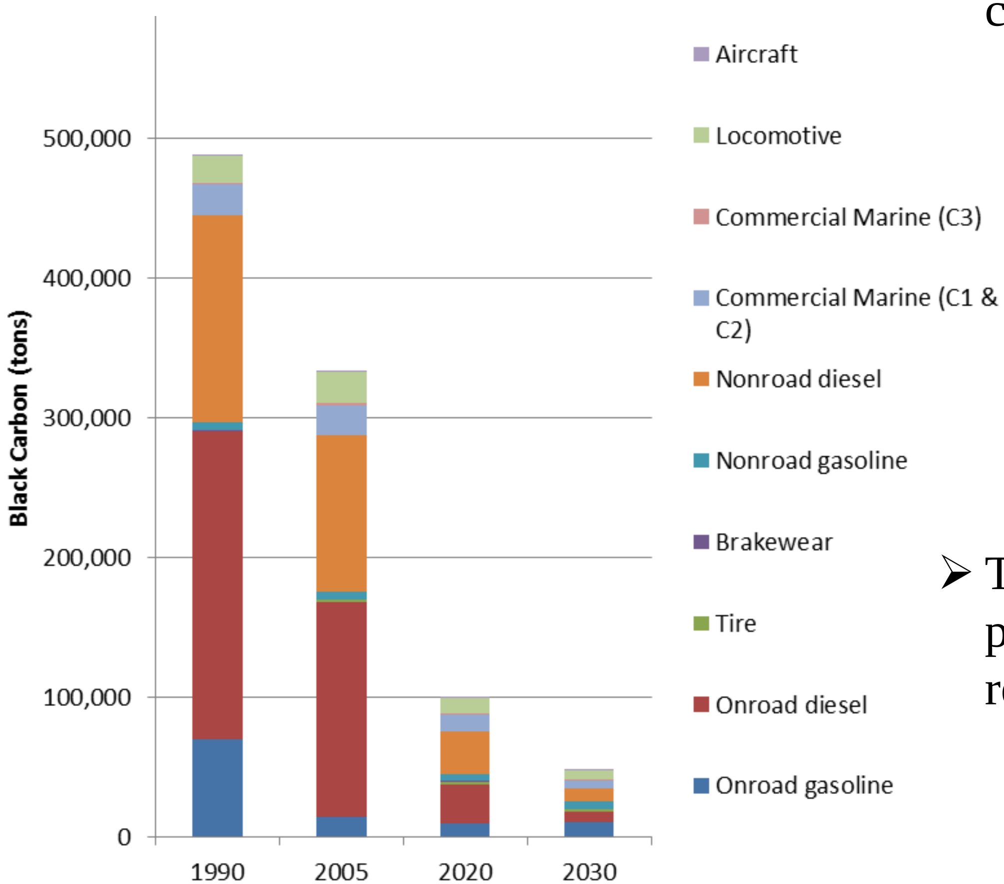
Mobile Sources

- U.S. mobile source BC comes mainly from diesels
- Gasoline exhaust is a smaller source of BC



U.S. Black Carbon Emissions from all Mobile Source Categories, 2005 (total 333,400 tons)

U.S. Mobile Sources

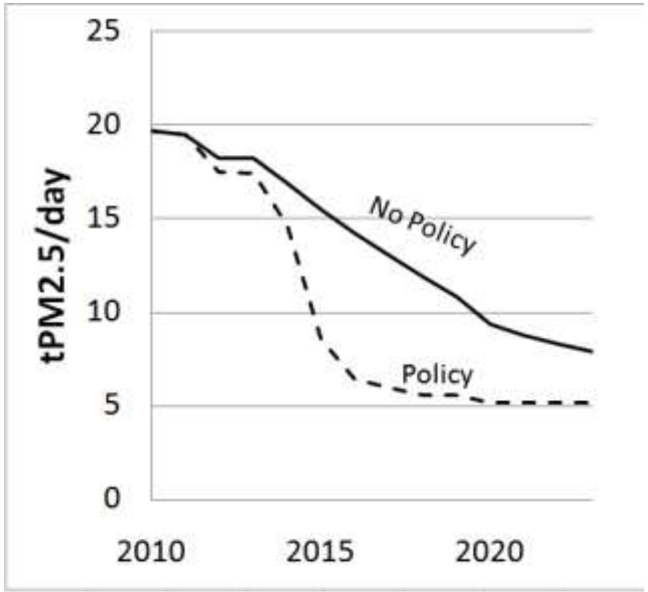


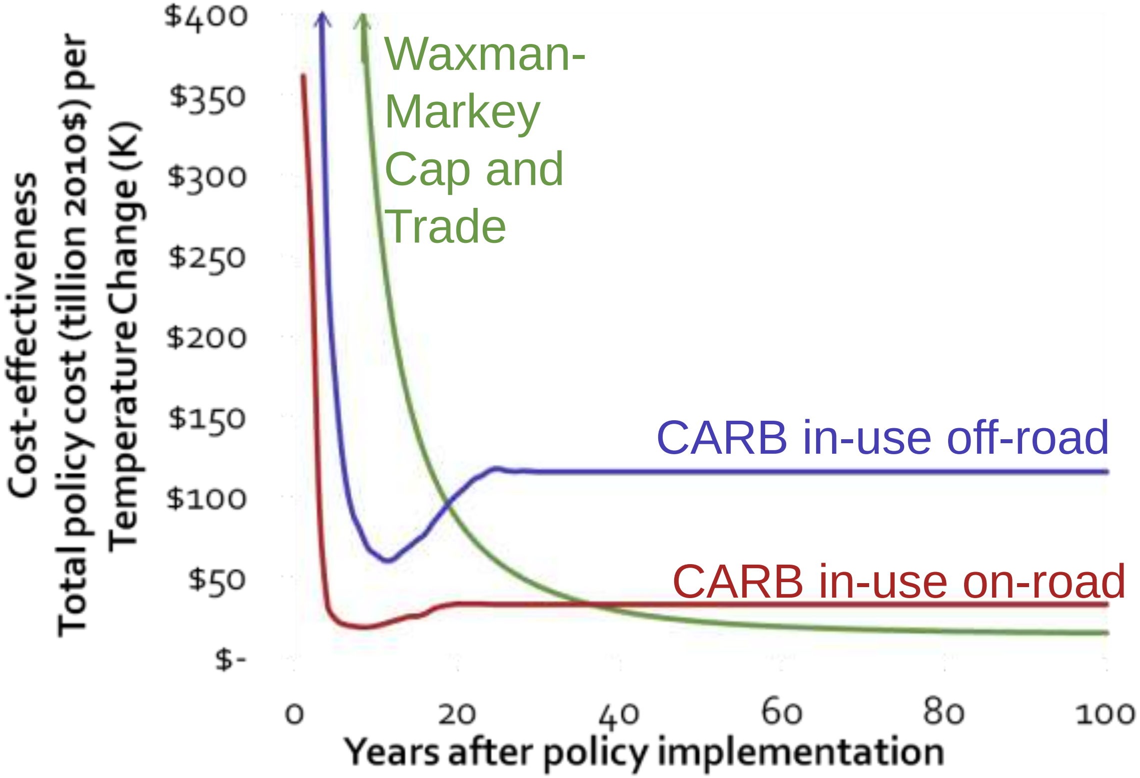
Emissions from U.S. Mobile Sources

- BC emissions from U.S. mobile diesel 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\$).

CARB's rules accelerate diesel turnover

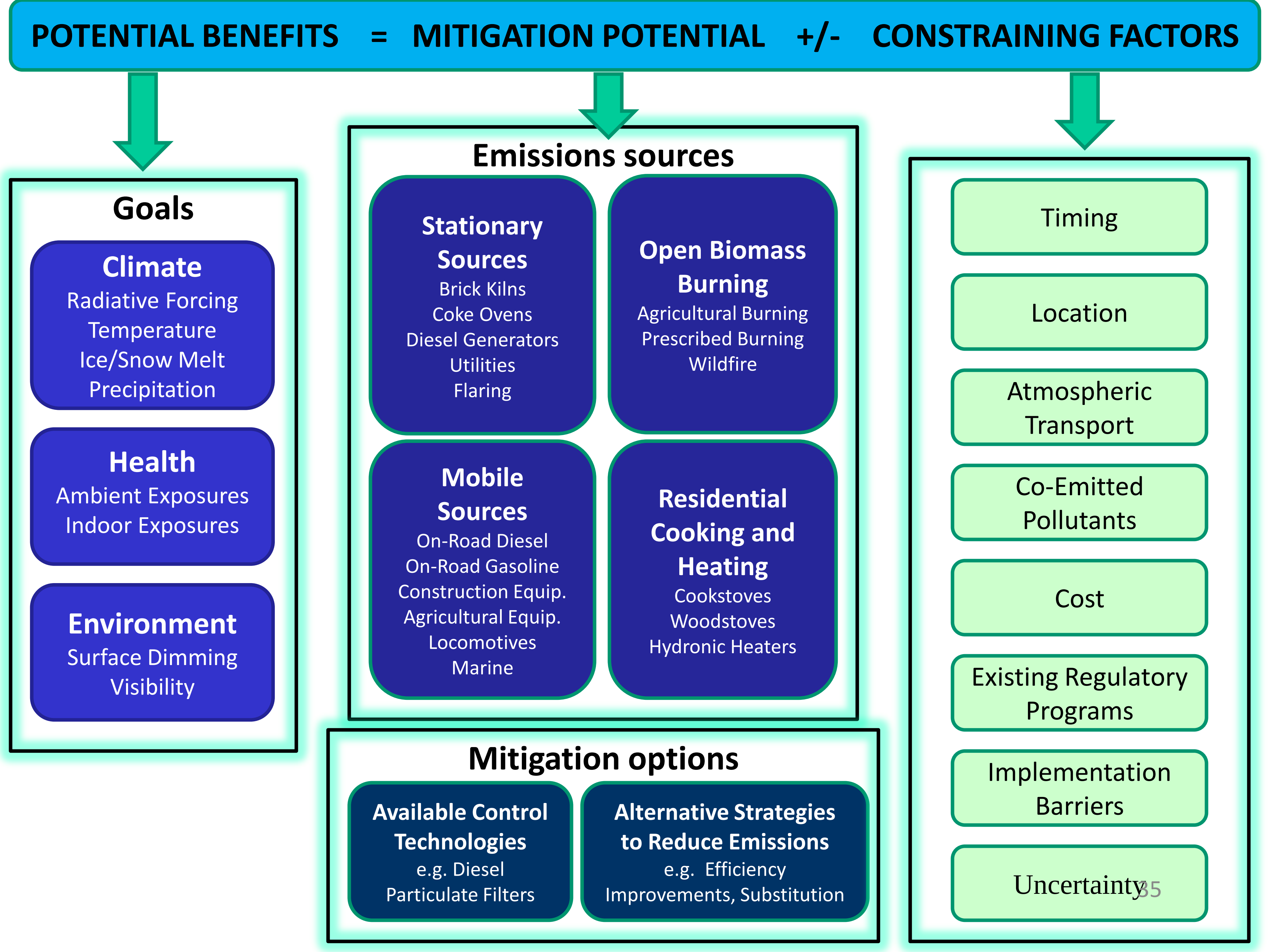
In-use policy approach





- ➢ CARB's truck and bus rule will result in accelerated turnover & rapid reduction of BC.

- ➢ To get near-term cooling, BC mitigation like diesel retrofit can be more cost-effective than CO2 measures; to get long-term cooling CO2 measure are most cost-effective.


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

EPA Black Carbon Initiatives

Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants

- Announced by Secretary Clinton and Administrator Jackson February 16, 2012
- Goal is to accelerate reductions in BC, methane, and HFCs
- Administered by UNEP
- Participants: 20 countries (including U.S., Canada, Sweden, Mexico, Ghana, Bangladesh, Colombia, Japan, Nigeria, the European Commission, Norway, World Bank, G-8) and several non-state partners
- Current initiatives:
  - Diesel emissions reductions (black carbon)
  - Brick kilns (black carbon)
  - Landfills (methane)
  - Oil and Gas (methane)
  - HFC alternatives
  - Two cross-cutting: National Action Planning, Financing

Global Alliance for Clean Cookstoves

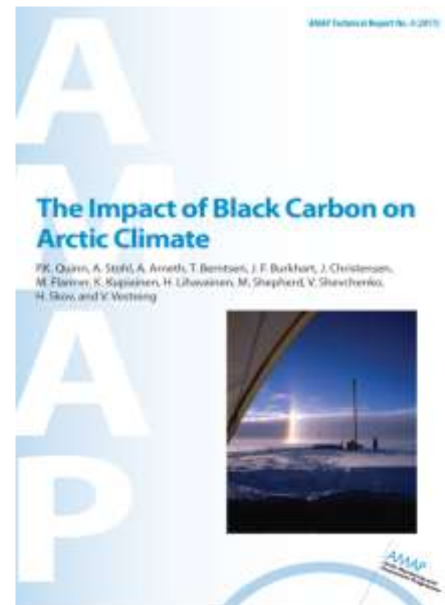
- Announced by Secretary Clinton in September 2010
- Administered by UN Foundation
- Includes over 450 partners, including 38 countries
- Goal: 100 million clean cookstoves adopted by 2020 by building a thriving market for clean cooking solutions
- Mission: Save lives, combat climate change, improve livelihoods, safeguard the environment
- In the process of planning an initiative to reduce BC from residential solid fuel use under the Climate and Clean Air Coalition Framework

Other International Efforts

Gothenburg Protocol

- In May 2012, the Convention on Long-Range Transboundary Air Pollution (LRTAP) adopted new PM requirements as part of revisions to the Gothenburg Protocol, including specific language on BC

Arctic Council



- Task Force on Short Lived Climate Forcers (2011)
  3-0a_TF_SPM_recommendations_2May11_final.pdf
- Arctic Monitoring and Assessment Program (AMAP): The Impact of Black Carbon in the Arctic (2011) (www.amap.no)
- Short-Lived Climate Forcers Project Steering Group (under the Arctic Contaminants Action Program (ACAP), see http://www.epa.gov/international/io/arctic.html)

International Maritime Organization (IMO)

- Considering whether to control BC emissions from ships (particularly in the Arctic)

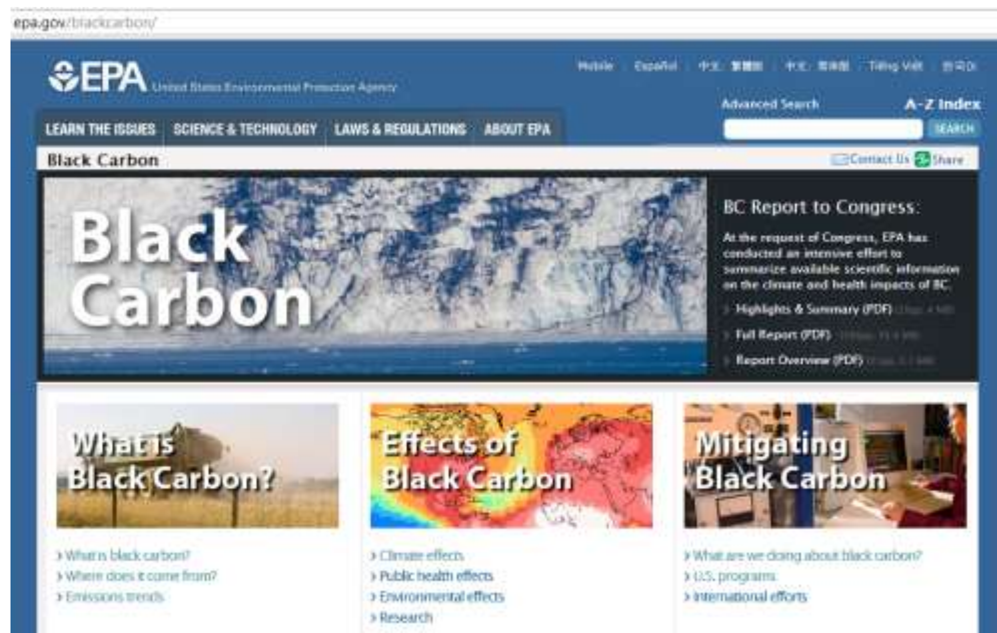
EPA Region 9 Black Carbon Symposium & other agency resources

San Francisco/ New York Black Carbon Symposium Resources:

http://epa.gov/region9/climatechange/blackcarbon/

Website on EPA's Report to Congress:

http://epa.gov/blackcarbon/



EPA Report to Congress Key Messages

- Black carbon emissions affect the Earth in a number of significant ways.
- Targeted reductions in black carbon (BC) emissions can provide significant near-term climate benefits, and the health and environmental co-benefits are very large.
- Effective control technologies and approaches are available to reduce BC emissions from a number of key source categories.
- U.S. BC emissions have been declining, and additional reductions are expected by 2030 due to controls on mobile diesel engines.
- Measurements indicate that ambient BC has declined and $PM_{2.5}$ air quality has improved due to these emissions reductions.
- Controlling direct $PM_{2.5}$ emissions from sources can be a highly effective air quality management strategy, with major public health benefits.

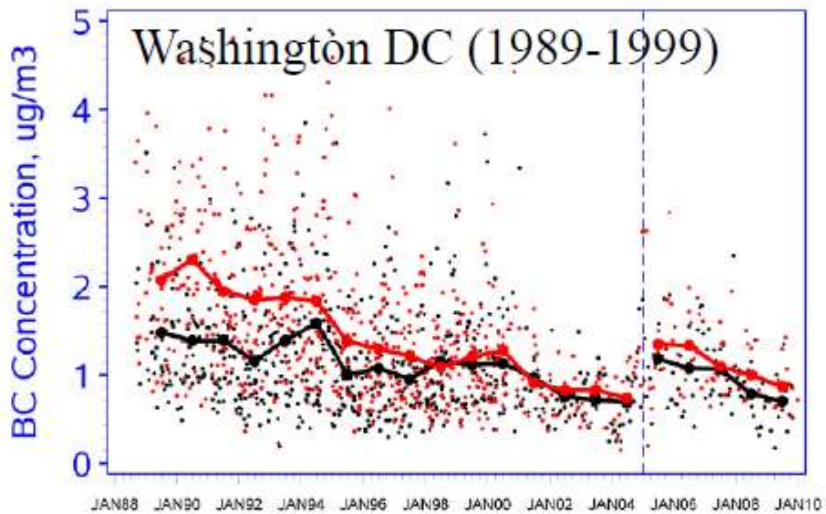
Source: Reuters

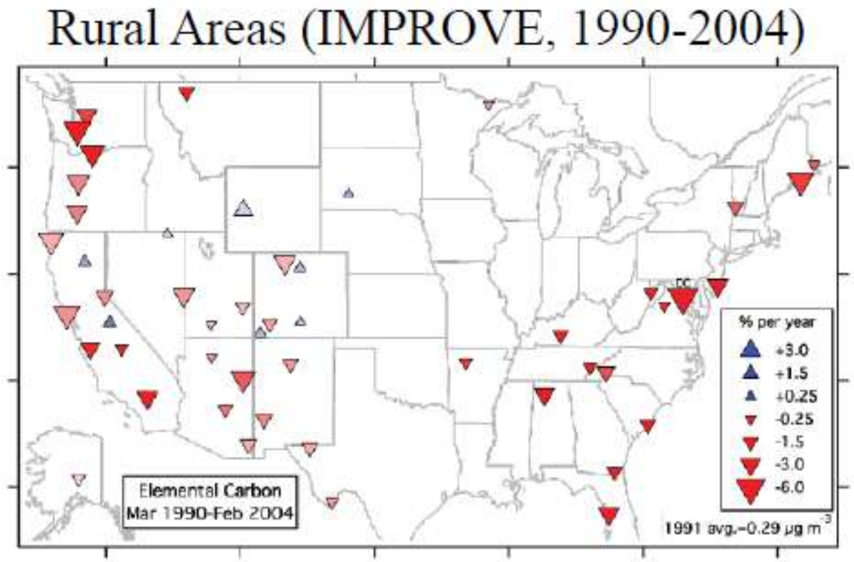
Some of my own concluding thoughts

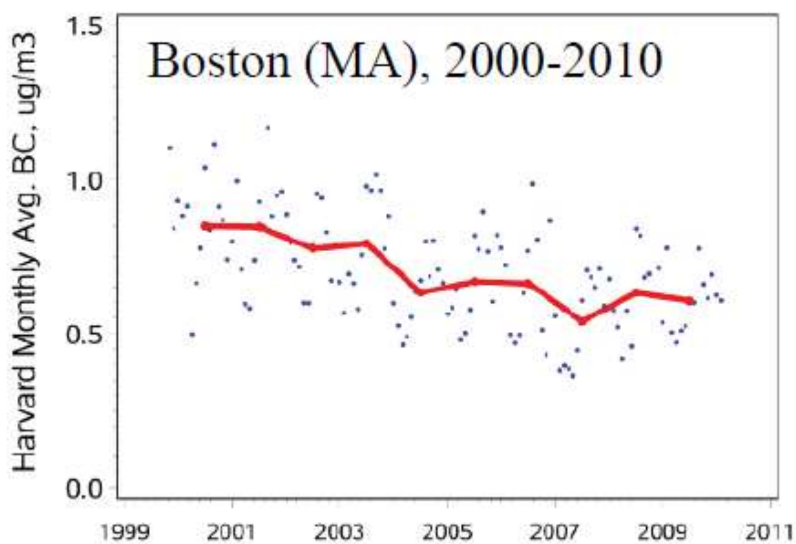
- Despite some remaining uncertainties, currently available information provides a strong foundation for mitigating BC
- The US and California have already done a lot to reduce BC through PM efforts; new engine standards will continue to drive down emissions
- To maximize climate benefit of PM health mitigation efforts, consider how much of the PM is BC and consider co-emitted species
- Choose a metric consistent with the values/goals of your agency; examine sensitivity to explore implications of remaining uncertainty.

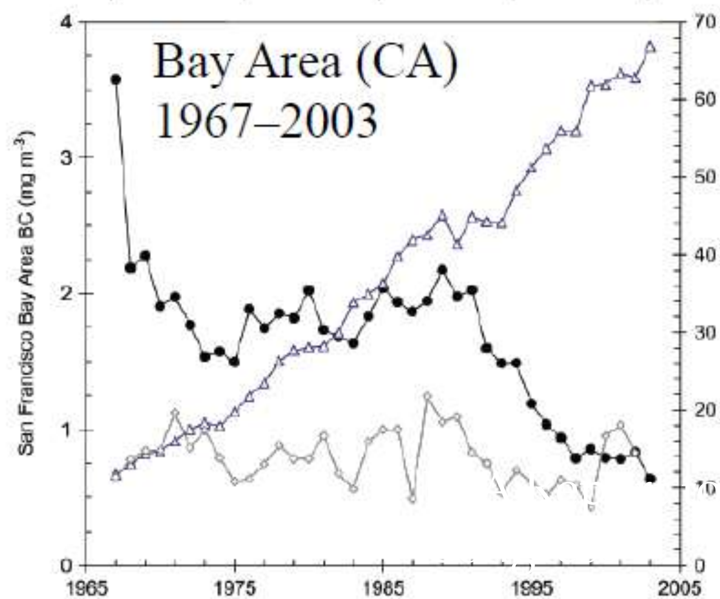
Appendix

What was the U.S. Trend in Ambient BC?









Ratio of OC to BC Varies by Emission Source Category

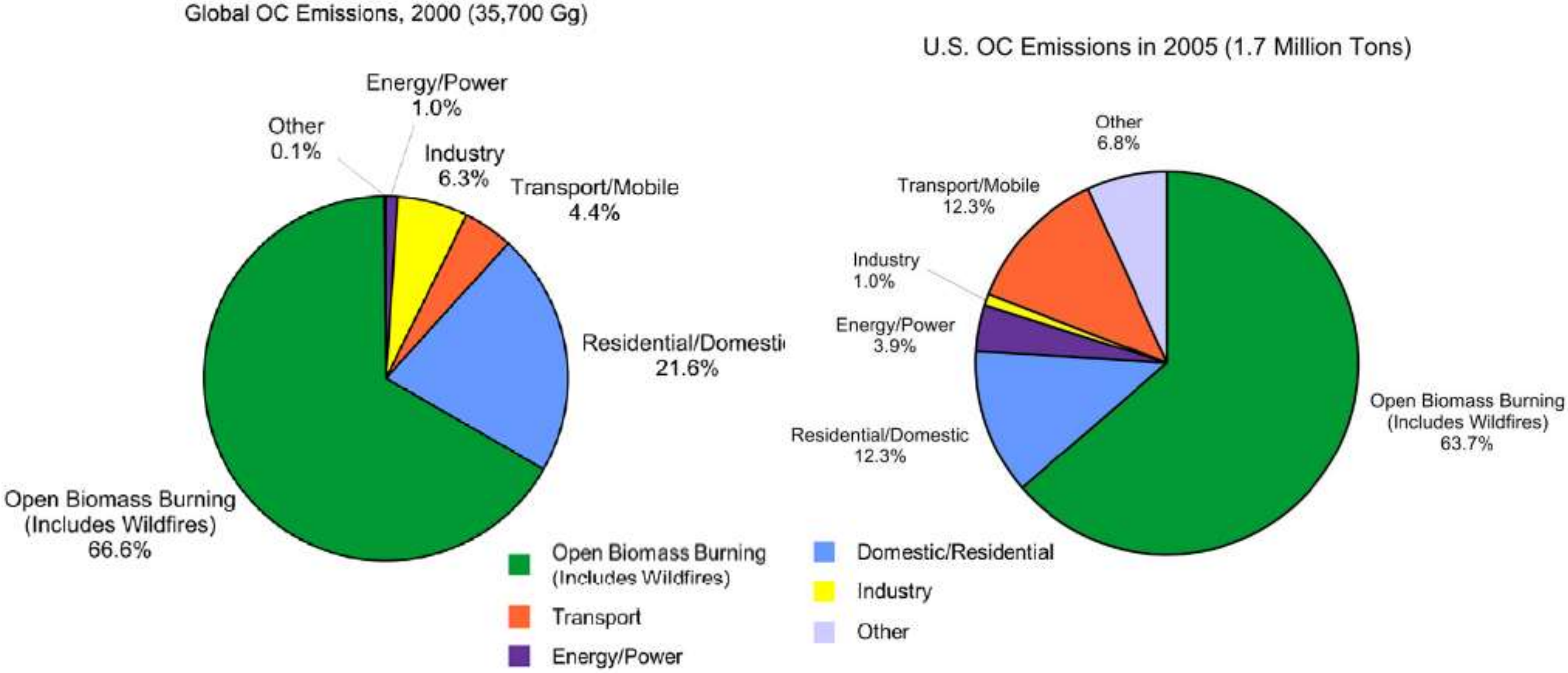
Mega* Source Category	PM2.5	BC	OC		OC/BC	BC/PM2.5
========================	==========	==========	==========		==========	==========
Open Biomass Burning	2,266,513	224,608	1,058,494		4.7	0.10
Residential	464,063	22,807	204,160		9.0	0.05
Energy/Power	712,438	43,524	65,138		1.5	0.06
Industrial	219,460	6,085	16,234		2.7	0.03
Mobile Sources	626,859	333,405	205,171		0.6	0.53
Other	1,232,123	6,743	112,967		16.8	0.01
	==========	==========	==========		==========	==========
Totals (Short Tons)	**5,521,456**	**637,172**	**1,662,164**		**2.61**	**0.12**
Gigagrams (Gg)	**5,009**	**578**	**1,508**			

➢ Mobile sources are the only category for which there is more BC than OC estimated to be emitted. This is largely due to the composition of diesel emissions. The OC:BC ratio is one of the indicators for climate mitigation purposes.

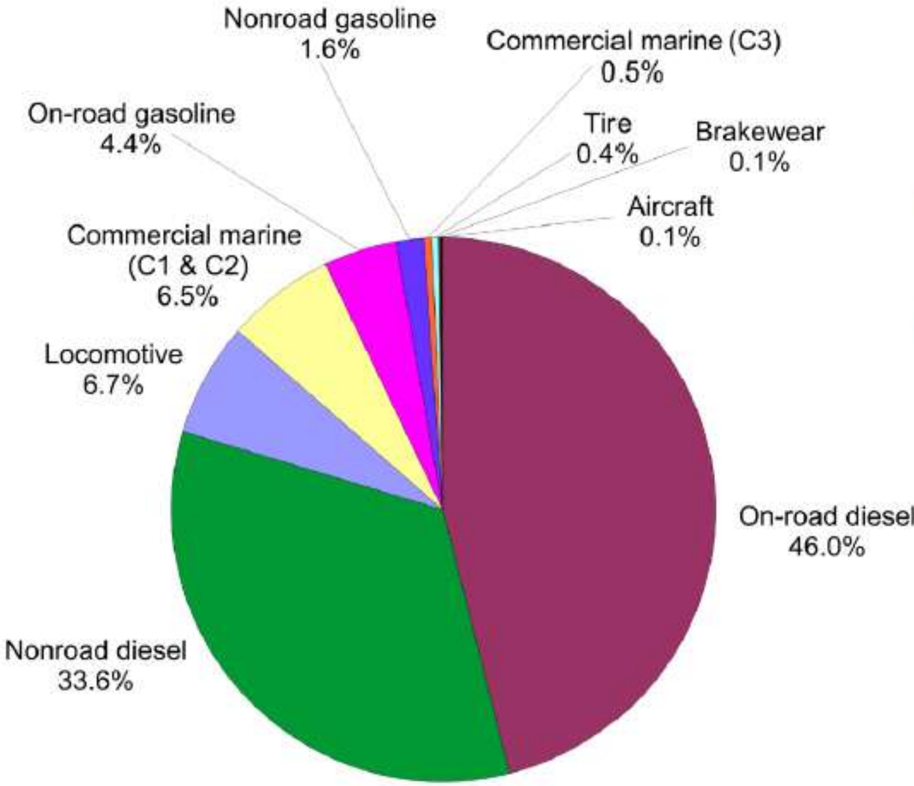
➢ Open biomass burning has significant BC emissions, but a lot more OC emissions.

➢ Nationally, in the US, about 12% of PM2.5 emissions is estimated to be BC. About 30% is co-emitted OC.

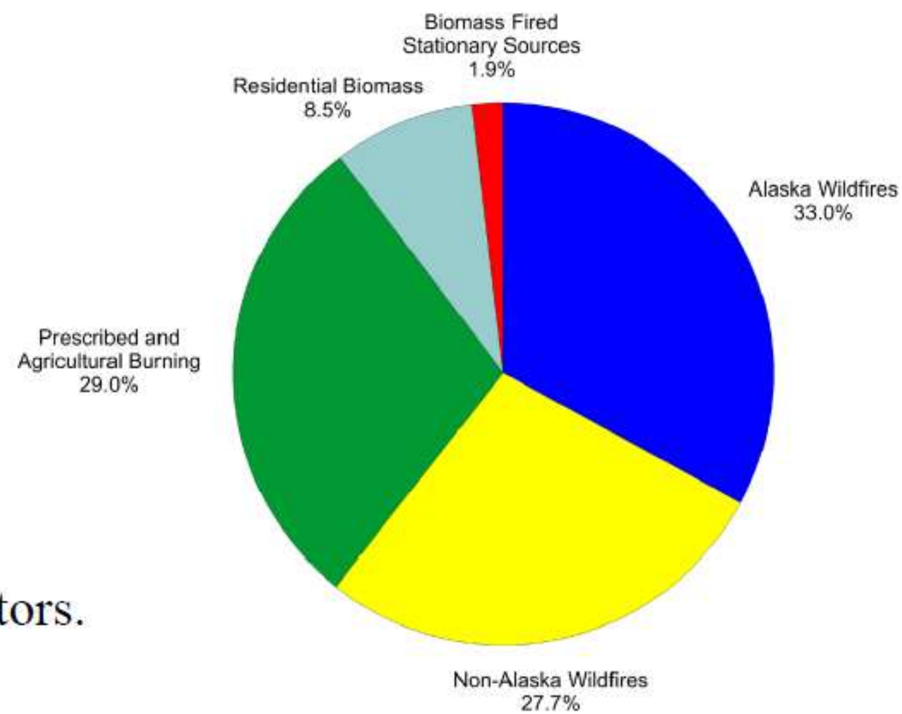
Organic Carbon Emissions - Global versus U.S.



- OC always co-emitted with BC, must be considered in any control and/or mitigation scenarios.
- Most of OC comes from burning, and is considered to be reflective (cooling).
- How much of OC is light-absorbing (warming BrC)?



- Mobile source BC dominated by diesels (~ 90% of total contribution).
- As diesels become more controlled, % of other sources will grow in future.



- Biomass burning BC dominated by prescribed and wild fires.
- AK wildfires particularly important in "bad" years, and even more important considering proximity to arctic areas.
- RWC and other sources small contributors.

From the Report to Congress…

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.

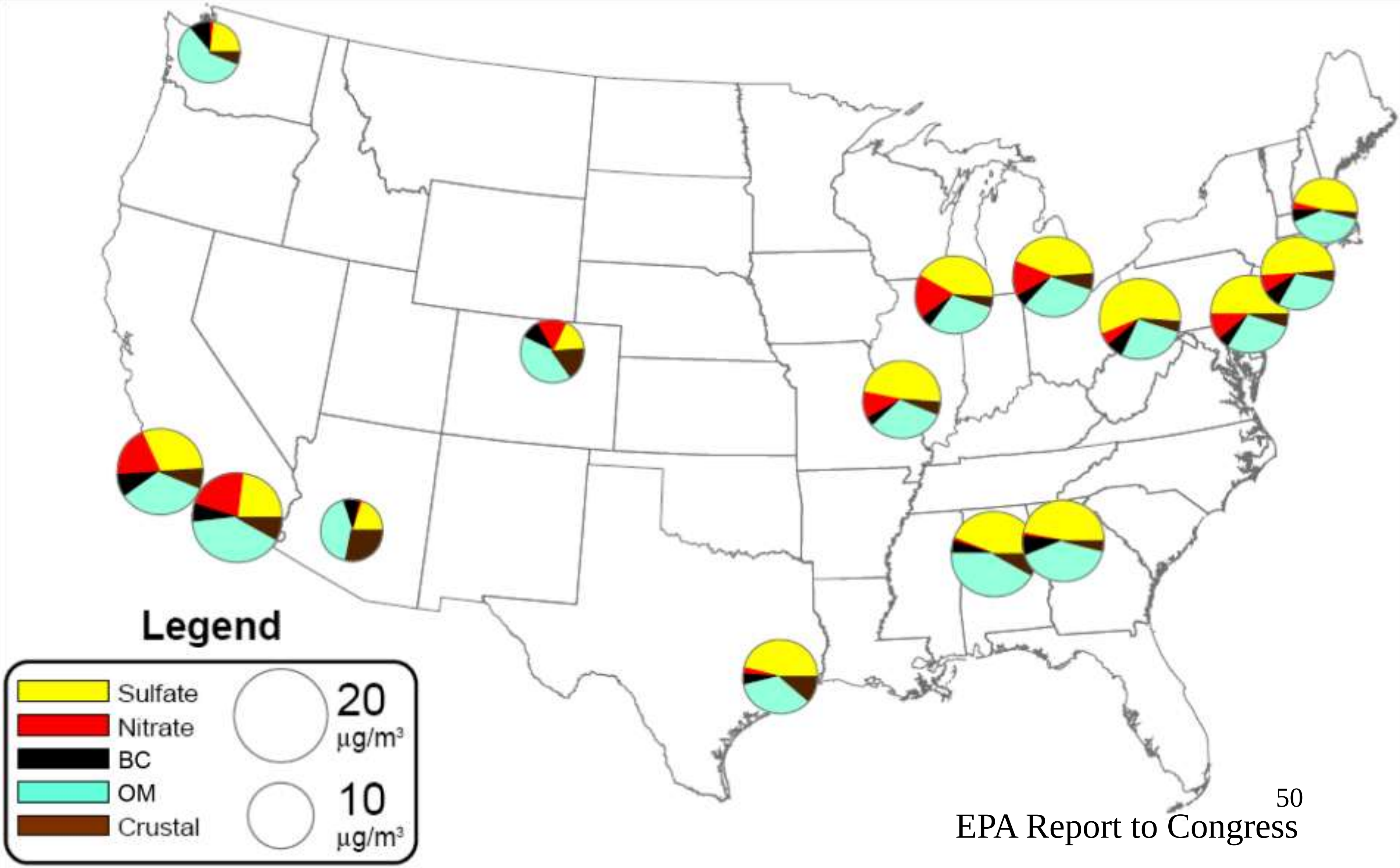
Soot, a complex mixture of mostly BC and OC, is the primary light-absorbing pollutant emitted by the

- BC is a component of I
and the most efficient abs
per unit mass.

- BrC is part of OC.

- Soot component of PM_2

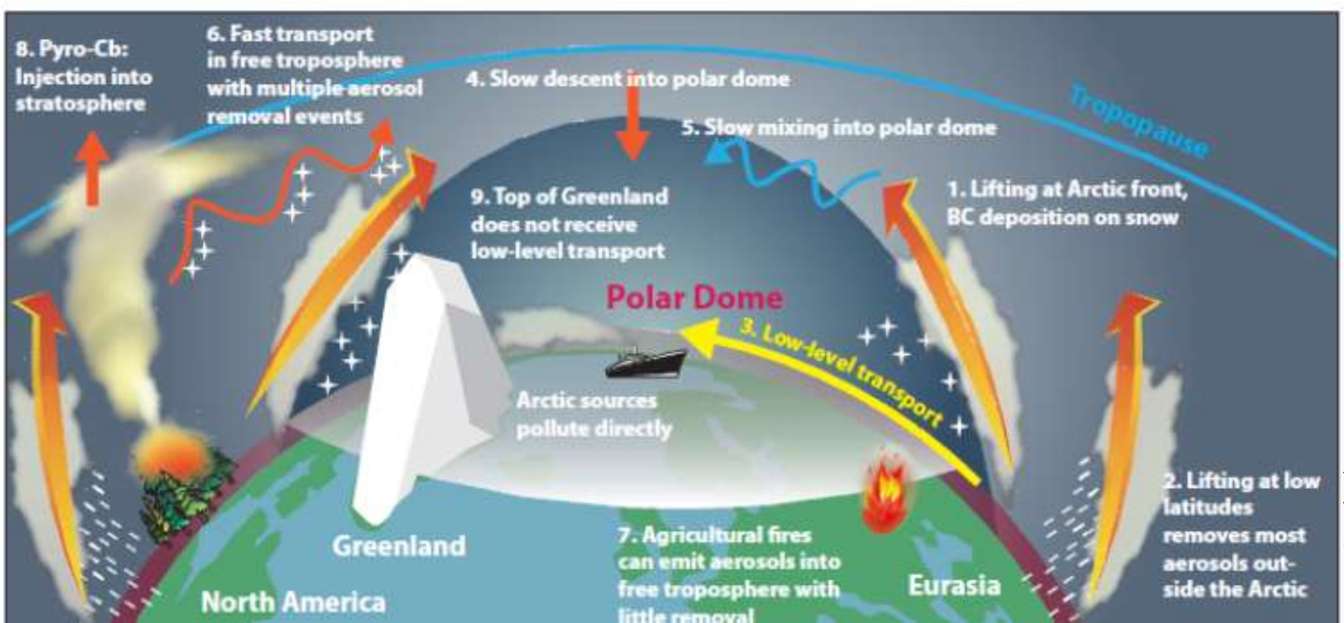
Composition of $PM_{2.5}$ for 15 Selected Urban Areas in the United States



EPA Report to Congress

Black Carbon Deposition Affects Surface Albedo

- BC deposition on snow and ice darkens the surface, and increases absorption of solar energy.
- Snow and ice in sensitive regions like the arctic and the Himalayas are especially at risk from BC deposition.
- BC in snow and ice may be more effective than well-mixed GHGs in warming the atmosphere:
  - Energy absorbed by BC in snow and ice goes directly into melting rather than dissipating throughout the atmosphere
  - BC may persist at the surface, contributing to longer-term warming, or
  - Snow and ice may melt, leaving behind a darker surface (such as rock or ocean)



Source: AMAP, 2011

EPA Report Congress

Indirect and Semi-Direct Effects on Clouds:

Black Carbon's effects on clouds are many, but understanding is low

- BC particles can lead to the formation of more, smaller water droplets in clouds.
  - Smaller droplets make clouds more reflective, producing a cooling effect.
  - Smaller droplets can also delay precipitation, increasing cloud lifetime, and extending the cooling effect.
- Smaller droplets in mixed-phase (clouds with liquid and ice droplets) can delay freezing, with uncertain implications for warming.
- BC in clouds can also contribute to cloud instability by absorbing solar radiation, and warming the cloud. This is called the "semi-direct" effect, and has uncertain implications for warming.
- BC in super-cooled liquid clouds can accelerate precipitation by acting as a nucleus for crystal formation, thereby shortening the lifespan of a cloud, and contributing to warming.

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Atmospheric Brown Clouds and Precipitation

- In high concentrations, and when combined with other pollutants, BC can form Atmospheric Brown Clouds (ABCs).
- BC in ABCs can contribute to surface dimming by absorbing and scattering incoming radiation.
- ABCs have been linked to a decrease in vertical mixing, which exacerbates air pollution episodes.
- ABCs may contribute to changes in precipitation patterns, including a slowing of th monsoon circulation over the Indian Ocean.

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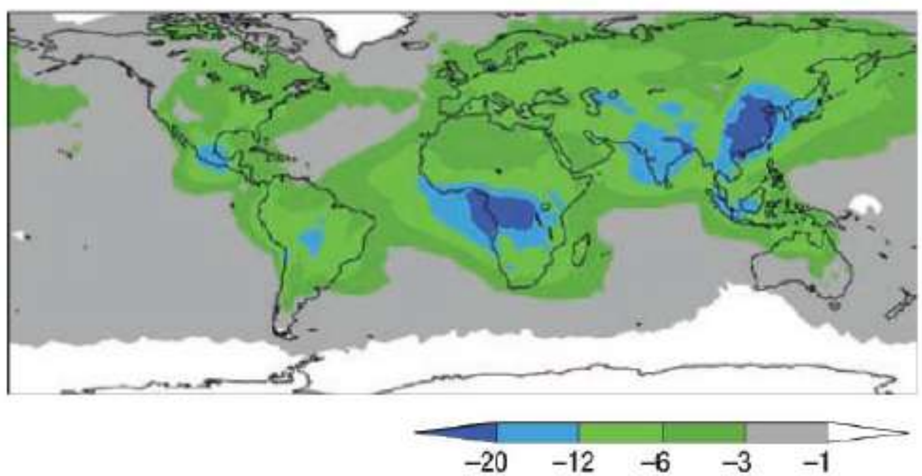
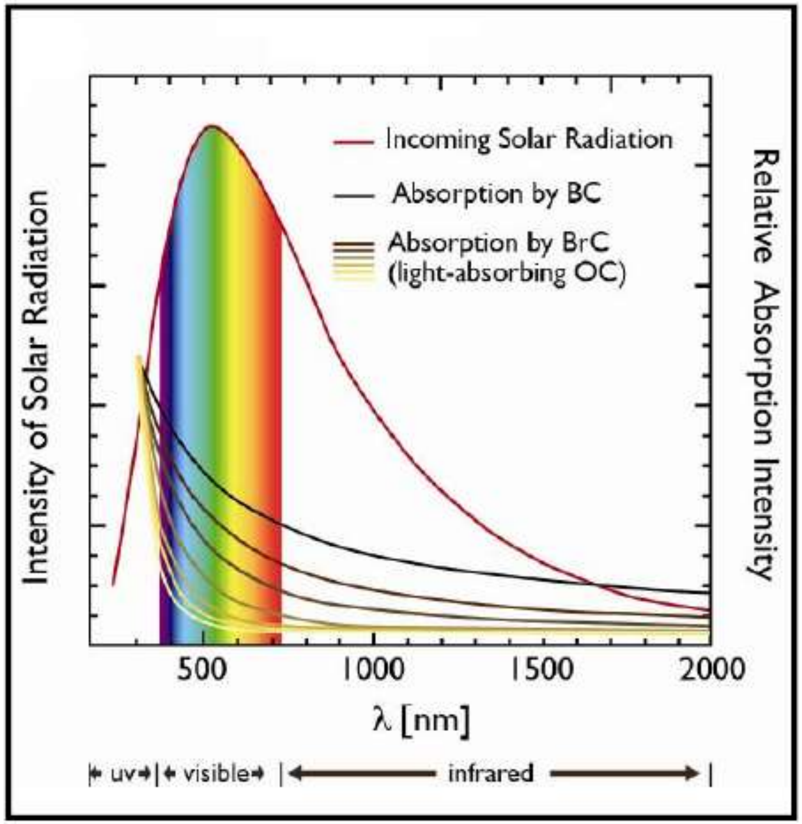


Ambient Atmospheric BC

- Ambient BC is the most strongly light-absorbing component of PM.
- Quantities of BC have a significant effect on local RF.
- Unlike long-lived greenhouse gases, BC has a limited atmospheric lifetime (on the order of days).
- BC does not become well mixed, and its effects are not easy to aggregate to the global scale.
- BC in the atmosphere can also contribute to surface dimming in the form of Atmospheric Brown Clouds.



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Analysis by activity

Only certain sectors or technologies within those sectors make good targets for mitigation for climate purposes: diesels, some industrial sources, some residential sources.

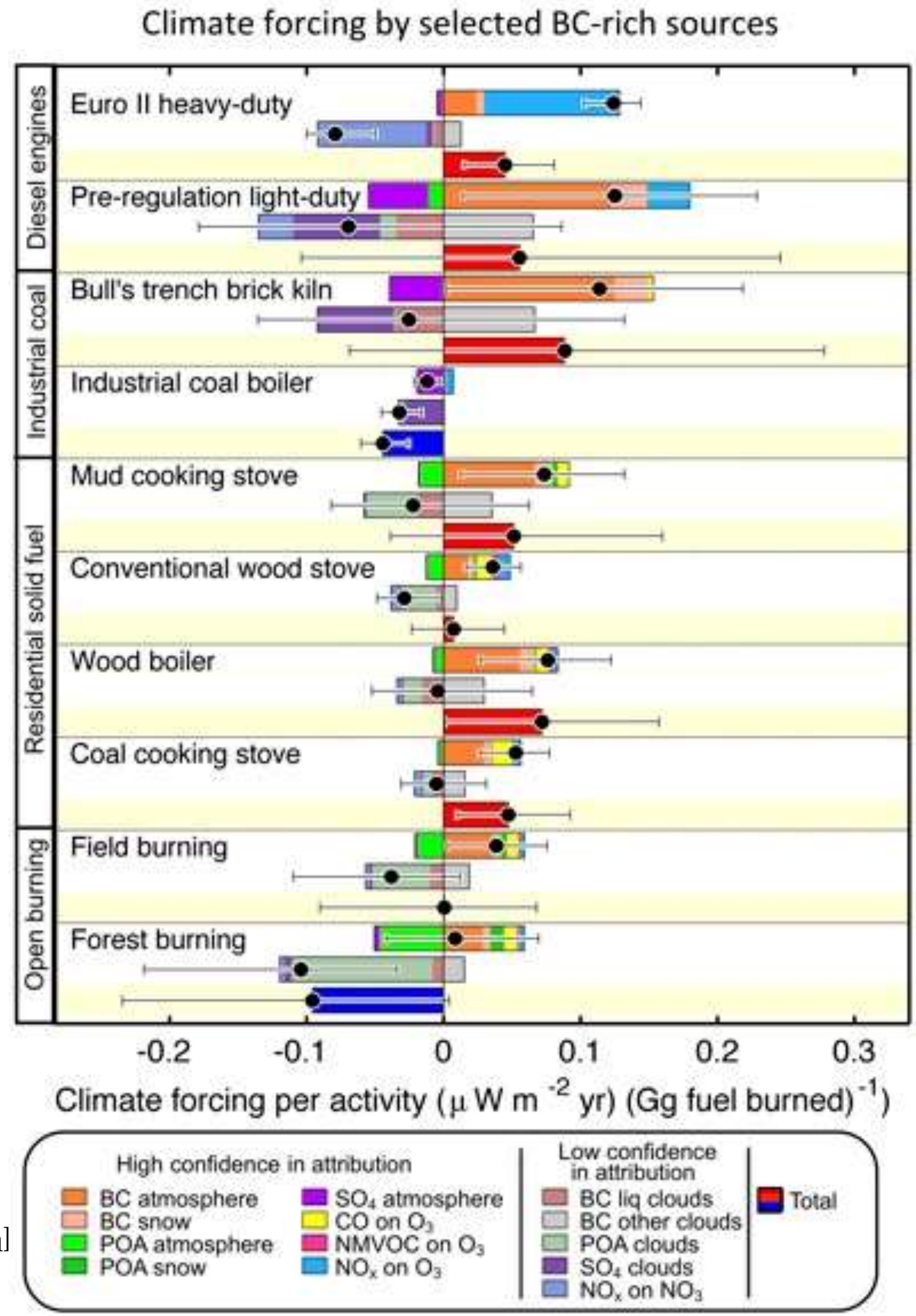
This graphic shows only very-short-lived species

Some mitigation techniques will not reduce all emissions equally

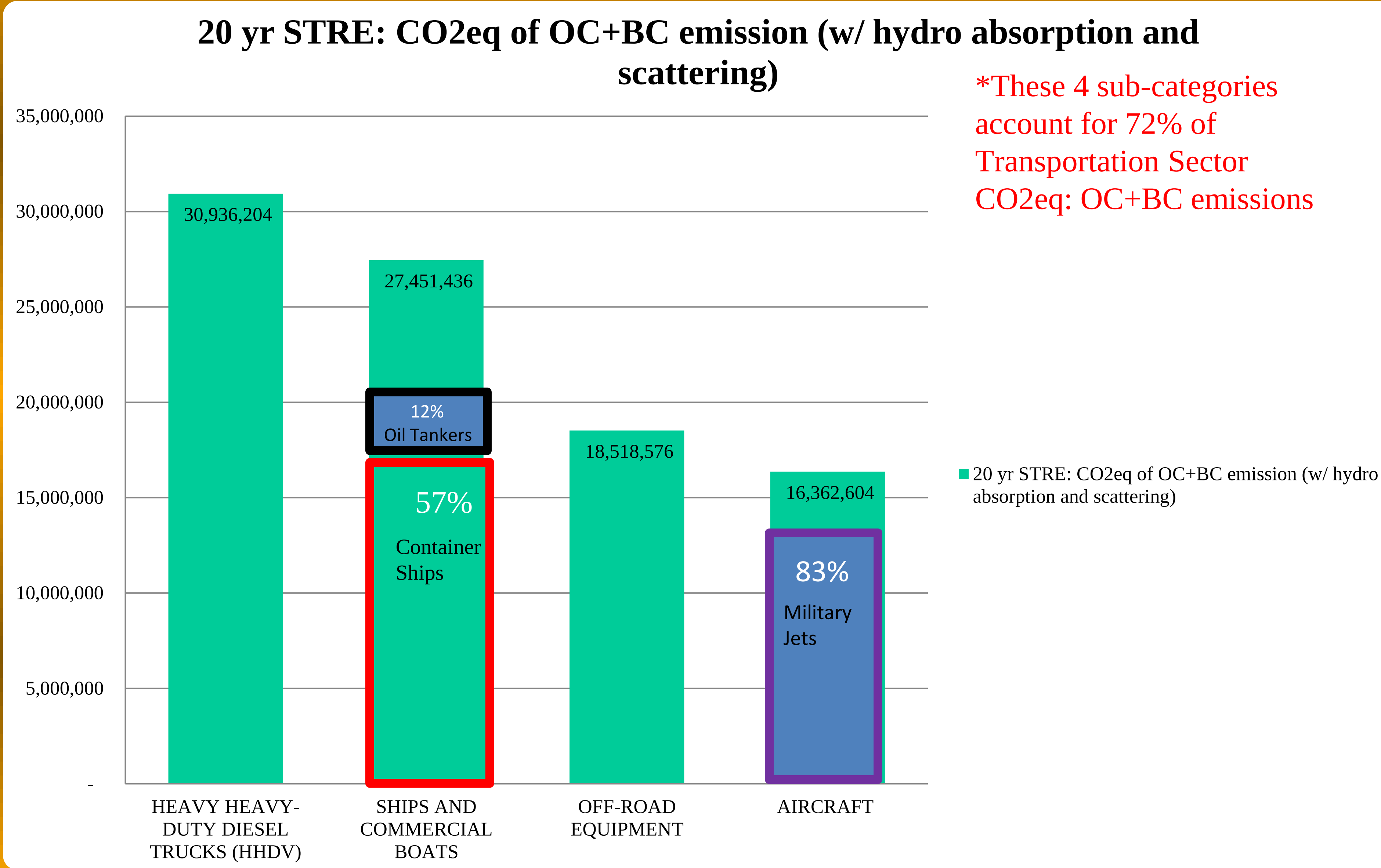
Global averages – local emissions may vary

Bond et al. *AGU* 2013

internal



Black Carbon Transportation sources in CA



U.S. Stationary Sources

- 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.

Reducing BC from Mobile Sources

- BC emissions from U.S. mobile diesel 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.
    - Standards are for PM and are "technology forcing."
    - Reductions estimated from emissions models used in regulatory packages
      - On road BC, OC, PM inventory from MOVES
      - Nonroad BC inventory from PM for NONROAD model
      - Locomotive, commercial marine, and aircraft emissions estimated separately from models
  - **Retrofit programs** for in-use mobile diesel engines, such as EPA's National Clean Diesel Campaign and the SmartWay Transport Partnership Program.
- EPA presently has minimal standards for gasoline PM; however, EPA VOC/other standards do reduce gasoline PM

Science-policy reports on short-lived climate forcers