

# Current Policies, Emission Trends and Mitigation Options for Black Carbon in the Arctic Region

## Draft White Paper by an Ad Hoc Working Group

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**28 April 2009**

\* The views of the authors do not necessarily represent those of the U.S. Environmental Protection Agency, the U.S. Department of State or of any other governmental body or agency

## **Executive Summary**

The 2007 IPCC Fourth Assessment Report noted that black carbon (BC) may exert a significant anthropogenic warming effect on the global climate. Since then an increasing number of modeling and sampling studies have strongly supported this warming effect. This is especially true in the Arctic and other snow-covered regions, where BC in the atmosphere absorbs more heat over these reflective surfaces; and once deposited, darkens snow and ice to lead to greater melting as well. The melting leads to greater exposure of the darker land and sea below, which in turn absorb more heat, and thus to additional warming and melting.

Current studies strongly point to diesel and open burning (both agricultural burning and wildfires) as the major sources of BC that reach the Arctic from the eight Arctic Council nations. These sources also comprise the greatest part of BC emissions in near-Arctic regions (north of approximately forty degrees latitude), including much of the European Union, Ukraine and China north of Beijing. With increased shipping expected in and near the Arctic due to sea ice loss, several studies also point to marine sources of BC as a major and growing future contributor to emissions. Oil and gas flaring and industrial sources may also contribute to BC emissions with Arctic impact; however the scale of emissions has not been studied sufficiently to determine if these constitute significant sources.

There is sufficient evidence to support the reduction of BC emissions from the identified sources (diesel, burning and marine) as a means to slow the rate of warming in the Arctic over the next few decades. Additional study is urgently needed to determine the impact of the potential sources (oil and gas flaring and industrial) and their most cost-effective mitigation measures. This paper begins to identify the most economically and technically feasible options that Arctic nations should begin to consider now in order to reduce near-term temperature rise through BC mitigation measures focused on these three sources. Significant health or other co-benefits are additional reasons to motivate early action.

These recommendations primarily include diesel engine measures (e.g., retrofits with particulate diesel filters) and biomass burning measures (e.g., management of springtime burning). Additionally, significant mortality and morbidity could be averted due to air quality benefits from particulate emission reductions.

## **Technical Summary**

Estimates from the Intergovernmental Panel on Climate Change and more recent studies suggest black carbon (BC) may be exerting a significant anthropogenic warming effect on the climate. More recently, concern has been raised about how BC may be contributing particularly to the high rates of observed warming and ice melt in the Arctic, primarily due to BC's darkening effect on snow and ice as well as its enhanced absorption above reflective surfaces. Mitigation of BC emissions therefore has the potential to slow the rate of warming in the Arctic in the next few decades. This paper attempts to identify the most economically and technically feasible BC mitigation options that can reduce near-term temperature rise. To identify these options, it is necessary to determine mitigation cost per ton of BC, and total inventories of BC emissions in the Arctic nations and globally. Because some of these sources are also significant contributors to organic carbon (OC) emissions, which have reflective and therefore cooling properties, it is necessary to identify and quantify co-emitted species. Additionally, because a number of policies that are currently implemented to reduce particulate emissions will yield significant black carbon reductions, it is necessary to include those policies in future projections and show the additional benefits that further mitigation can contribute.

The major sources of BC in the eight Arctic Council nations (the United States, Canada, Iceland, Norway, Sweden, Finland, Denmark, and Russia) are diesel transport and open burning (both agricultural burning and wildfires). Diesel particulate emissions, with low fractions of organic carbon, are the emissions that are likely to have the largest net warming impact. However, new diesel vehicles in the US and Europe are already required to have significant particulate controls. Therefore, to identify additional opportunities for BC reduction, this analysis examines the potential for retrofitting existing vehicles that were built before the new particulate rules took effect. In the case of open burning, large co-emissions of organic carbon make it unclear whether particulates from open burning lead to net warming. However, the cooling properties of organic carbon loading are not as significant over snow-covered regions. Therefore there may still be a net Arctic climatic benefit to controlling agricultural burning in high northern latitudes, especially during the spring melt season.

Particulate filter retrofits of the pre-2007 U.S. diesel fleet could yield, by themselves, about 115,000 tonnes of BC reduction over the lifetime of the vehicles for less than \$15,000 dollars per tonne BC (or about \$1.5 billion total expenditure to retrofit about half a million vehicles), of which about 16,000 tonnes of BC would be reduced in the first year after the retrofits. It is more difficult to assign economic costs to certain agricultural measures, but estimates indicate that for about \$15,000 dollars per tonne BC 28,000 tonnes of BC can be reduced per year from agricultural burning in the US, though those reductions would be accompanied by a reduction of about 165,000 tonnes of OC. A recent study by Rypdal et al. (2009) showed economy wide potential BC abatement from contained combustion starting in the year 2030 for \$15,000 of about 30,000 tonnes of BC per year in North America, less than 10,000 tonnes in the EU-17, 20,000 tonnes in the rest of Europe, and less than 20,000 in Russia. The study notes that large sources (100s of kilotonnes) of inexpensive BC mitigation measures may be available in southeast and centrally planned Asia.

Using some estimations of GWP metrics in the literature, \$15,000 dollars/tonne BC yields a similar carbon equivalent price to the EU ETS carbon price. However, there is still significant controversy about the appropriate means of estimating the CO<sub>2</sub> equivalent value of very short-lived particles, and the appropriate uses of these metrics. However, using this GWP of about 900, the above 115,000 tonnes of BC reductions would be equivalent to about 104 megatonnes of CO<sub>2</sub> equivalent reductions over the lifetime of the vehicles.

This report concentrates on the Arctic nations. A priori, per ton emissions from those nations are expected to have the largest impacts on Arctic climate. Additionally, the report considers all emissions north of 40 degrees (the near Arctic regions), with more detail for Europe both because

of data availability and indications that European emissions are a large contributor to Arctic deposition. While marine shipping contributes only about 2% of global BC emissions and warming from these emissions is counteracted by co-emissions of sulfur oxides, the sector has potential for disproportionate Arctic impacts because of the possibility of additional high latitude shipping routes opening as summer Arctic sea ice levels decrease. Emissions outside the Arctic region can be transported to the Arctic as well.

Finally, it is important to note that because BC is a component of PM, BC mitigation options will reduce PM<sub>2.5</sub> levels with attendant health benefits.

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## 1. Introduction

The Arctic Monitoring and Assessment Program (AMAP) Workshop on Non-CO<sub>2</sub> Climate Forcings (Oslo, 15-16 September 2008) recommended consideration of forming a workgroup to evaluate feasible mitigation options and pan-Arctic implementation strategies for black carbon and other short-lived climate forcers. This research paper is a first pass at developing such an evaluation. Using the Bluestein et al. (2008) paper presented at the Oslo workshop as a starting point, this working paper is providing further detail on a number of points.

- Up-to-date inventories of current black carbon emissions
  - Focusing on near-Arctic regions
  - Including a discussion of remaining uncertainties
- Projected BC emissions in the next several decades, taking into consideration
  - current relevant policies already in place for black carbon (BC)
  - near- and medium-term implications of these policies for BC and co-emissions of other pollutants, including OC
  - Other factors (turnover, etc.) that will influence the projections
- the identification of opportunities for additional and accelerated BC reductions
- the estimated costs and feasibility of these BC mitigation options
- possible policy options that could deliver these mitigation options
- discussion of most promising options considering costs, implementation feasibility, and benefits to the Arctic

While this working paper has focused on the mitigation questions, rather than on science questions, continuing work is required to determine the climate benefits, particularly the surface temperature response of individual mitigation strategies for the Arctic. This paper reports on the most recent studies and results regarding these scientific questions, as well as summarizing key points from the AMAP Technical Report (Quinn, 2008).

We expect the Arctic Ministerial Declaration in April to recommend development of analyses and specific mitigation recommendations for the Arctic Ministers to consider in 2011. This paper, while not an official AMAP product, can therefore inform the proposed mitigation activities within the Arctic Council context and following the April 2009 Ministerial meeting.

## 2. General science background

The Arctic has warmed at twice the global rate over the past 100 years (IPCC 2007). Temperatures in virtually all parts of the Arctic increased between 1966 and 2003, with trends exceeding 1 to 2 °C/decade in northern Eurasia and northwestern North America (Arctic Climate Impact Assessment (ACIA) 2004). This warming has been accompanied by an earlier onset of spring ice melt, a lengthening of the melt season, and increasing discharge from the Greenland ice sheet. Summer sea ice extent has decreased by 40% since measurements began in 1979, and in 2007, it dropped to its lowest level resulting in the first recorded complete opening of the Northwest Passage (NSIDC 2007; Perovich, Richter-Menge et al. 2008). A number of climate models predict its complete disappearance by 2040 (Perovich and Richter-Menge 2009; Polyak 2009; Wang and Overland 2009).

The impacts of ice loss include reduction of the Earth's albedo, the extent to which it reflects the sun's radiation. As warming causes greater amounts of snow to melt, bare sea ice and eventually dark ocean water are exposed, which absorb more radiation. This positive snow-albedo feedback leads to further warming and is one of the reasons that the Arctic is highly sensitive to global warming. The earlier onset of spring melt observed in recent years is of particular concern as this is the season of maximum snow-albedo feedback (Hall and Qu, 2006).

Increases in Arctic temperatures will also lead to changes in Arctic flora and fauna including the sea-ice biomes and predators higher in the food chain. These shifts will lead to large changes in the lifestyle of indigenous peoples, and may be devastating for polar bears, ice-dependent seals, and people who depend on these animals for food (Quinn, Bates et al. 2008). This warming and melting has implications beyond the Arctic (ACIA, 2004), as melting of Arctic land-based glaciers is one of the factors contributing to global sea-level rise.

Arctic warming is primarily a manifestation of global warming and the most important long-term strategy for preserving the Arctic is to slow and eventually reduce the atmospheric buildup of CO<sub>2</sub> concentrations. However, because of the long lifetime of CO<sub>2</sub> in the atmosphere, even large and swift reductions in emissions may not achieve the reductions in atmospheric concentrations needed to delay rapid and perhaps irreversible change in the Arctic. However, CO<sub>2</sub> is not the only climatically important species contributing to warming in the Arctic. Several shorter-lived<sup>1</sup> pollutants, including BC, methane and tropospheric ozone, may be collectively responsible for as much temperature impact in the Arctic as CO<sub>2</sub> (Quinn, 2008). Addressing these pollutants has the advantage that emissions reductions will be felt much more quickly than reductions of longer-lived gases.

Black carbon or “soot” is the shortest-lived of these pollutants, remaining in the atmosphere only days to perhaps weeks. It is comprised of small dark particles that remain after incomplete combustion of fossil fuels or biomass. Black carbon warms the Arctic in two ways. First, as an aerosol, it absorbs solar radiation, heating the atmosphere and contributing to overall global and Arctic warming. Second, the deposition of BC onto ice and snow in the Arctic darkens the surface, increasing the absorption of radiation (Warren and Wiscombe 1980; Flanner, Zender et al. 2007). This BC-snow albedo effect, leads to warming of the lower atmosphere and melting of snow and ice.

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<sup>1</sup> Long-lived gases generally refer to gases that remain in the atmosphere long enough to become globally well mixed throughout the entire global atmosphere. This requires an atmospheric lifetime of approximately one year. Methane has an atmospheric lifetime of roughly a decade and therefore becomes globally well mixed, but most other greenhouse gases have much longer atmospheric lifetimes, which is why methane is also referred to as “short-lived.”

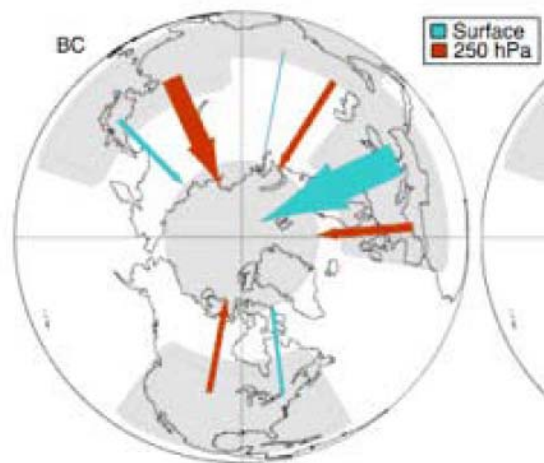
According to Quinn et al. (2008), once BC has been deposited on glaciers, it has lasting impacts. First, BC deposited directly on glacier ice tends to remain for years before being removed by surface run-off processes. Second, BC entrained in snow accumulation on large glaciers and ice caps is gradually buried and is transported downward due to ice flow. The ice flow eventually transports the BC out of the melt zone where it is once again exposed and can absorb solar radiation.

There is some uncertainty in the estimates of the radiative forcing that is caused by BC. The IPCC estimates that BC is responsible for  $0.34 (\pm 0.25) \text{ Wm}^{-2}$  in globally averaged direct radiative forcing, taking into account all major sources, and the BC-snow albedo effect is responsible for an additional  $0.1 (\pm 0.1) \text{ Wm}^{-2}$ , bringing the total to  $0.44 \text{ Wm}^{-2}$ . A more recent publication by Ramanathan and Carmichael (2008) suggests that the globally averaged direct radiative forcing alone may be  $0.9 \text{ Wm}^{-2}$ . Black carbon is likely to be an even larger relative contributor to Arctic warming than it is globally. Shindell et al. (2009) estimate that black carbon contributed 0.5 to 1.4 °C warming in the Arctic since 1890, compared to about 2.3 °C overall warming north of 60 degrees latitude in that timeframe.

Black carbon is often co-emitted with other substances. This is particularly true of organic carbon which is also a product of incomplete combustion. Organic carbon and sulfate particles in the atmosphere have a direct cooling effect due to their reflective nature. The IPCC estimates the globally averaged radiative forcing from the OC direct effect at  $-0.19 \text{ Wm}^{-2}$  and from the direct sulfate effect at  $-0.4 \text{ Wm}^{-2}$ . Additionally, hygroscopic aerosols, especially sulfates, can serve as nucleation sites for cloud droplets, leading to smaller more numerous drops and therefore higher reflectivity. This “cloud albedo effect” (or first indirect effect) is estimated to be responsible for  $-0.7 \text{ Wm}^{-2}$ , with significant uncertainty, and attribution of the effect to different components is not yet clear. Other indirect effects are even less well quantified. These effects include the “cloud lifetime effect” because smaller droplets are less likely to rain out, and the “semi-direct effect,” where heating due to BC causes cloud burn-off. The hydrological effects from these lifetime and semi-direct effects have direct non-temperature consequences in addition to leading to changes in radiative forcing. Internal and external mixing of the different species can lead to changes in both radiative and hygroscopic nature, complicating the estimation of radiative effects. For example, absorption by BC within sulfate aerosols is a factor of 2–2.5 greater than by BC in free air (Chylek, Lesins et al. 1996; Sato, Hansen et al. 2003). Additionally, some carbonaceous particles are “brown” – not as absorbing as black carbon, but not as reflective as standard organic carbon (Alexander, Crozier et al. 2008).

### ***Transport of BC to the Arctic***

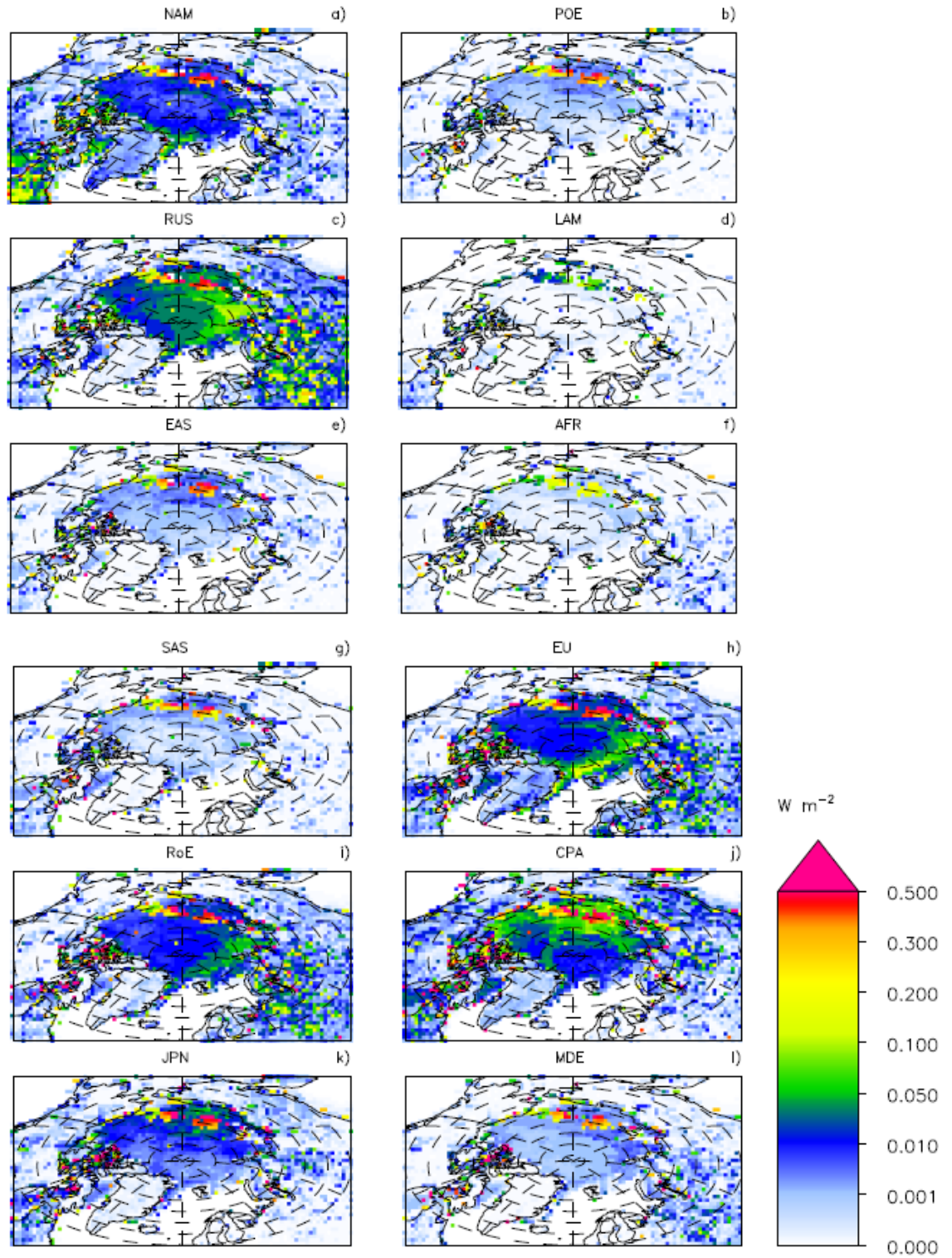
While some BC is produced in the Arctic itself, e.g. by ships traveling through the region, most is transported from elsewhere. Understanding this transport is important for determining which BC emissions contribute the most to Arctic warming. Transport has been studied both by modeling work (Figure 1) and by experimental work (McConnell, Edwards et al. 2007). From these studies, it appears that European emissions have a large impact on deposition of BC to the Arctic surface, excluding Greenland, which is more sensitive to emissions from North America. Transport is seasonally dependent, with studies suggesting that transport to the Arctic is greatest during the spring and summer (with the exception of European emissions deposited to the surface, which reach a maximum in boreal winter), which is also the season in which the efficacy of BC is largest (Shindell, Chin et al. 2008).



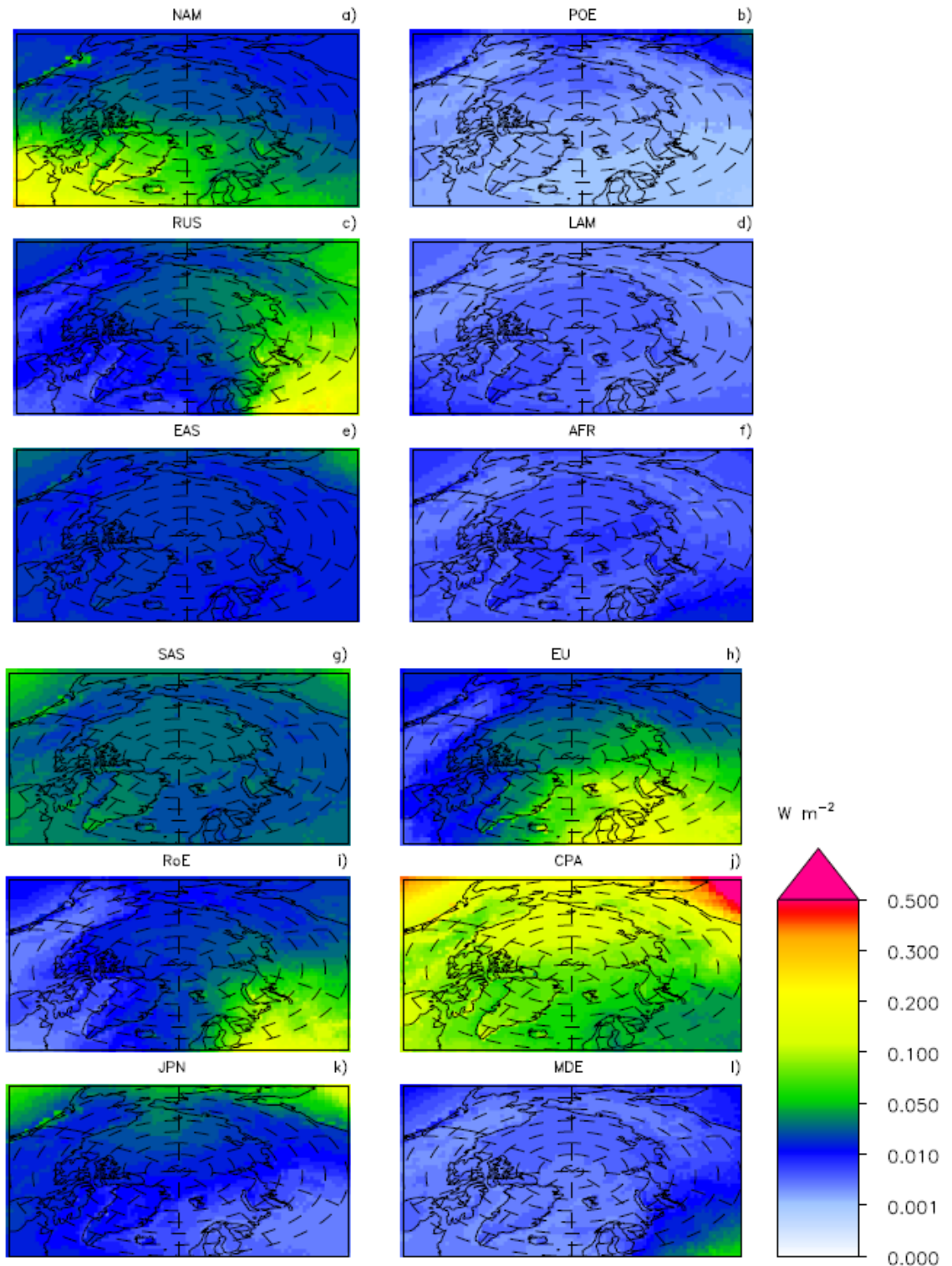
**Figure 1 Relative importance of source regions to annual mean Arctic concentrations at the surface and in the upper troposphere (250 hPa) for the indicated species. Values are calculated from simulations of the response to 20% reduction in anthropogenic emissions of precursors from each region . Arrow width is proportional to the multimodel mean percent contribution from each region to the total from these four source regions (Shindell et al., 2008). (from Quinn et al. 2008)**

Another study using the global aerosol transport model Oslo CTM2 showed that the contribution to the BC on snow and ice albedo impact in the Arctic is mainly from emissions from NAM, EU17, RoE, RUS and CPA (Figure 2 and Figure 3) (Rypdal, Rive et al. 2009).

**Figure 2 Radiative forcing of BC impact on snow and ice surface albedo effect for emissions from NAM a), POE b), RUS c), LAM d), EAS e), AFR f), SAS g), EU17 h), RoE i), CPA, j) JPN k), MIDE l), All regions m).**



**Figure 3** Direct radiative forcing of BC for emissions from NAM a), POE b), RUS c), LAM d), EAS e), AFR f), SAS g), EU17 h), RoE i), CPA, j) JPN k), MIDE l), All regions m).



### ***Health Effects of Particulate and Black Carbon Emissions***

Black carbon is a component of fine particulate matter. Particulate matter (PM<sub>2.5</sub>) has been regulated based on significant evidence and numerous health studies demonstrating that serious health effects are associated with exposures to elevated levels of PM<sub>2.5</sub>. An Integrated Science Assessment produced by the EPA (ISA, 2008) includes evidence that a causal relationship exists between short-term exposure to ambient concentrations of PM<sub>2.5</sub> and cardiovascular morbidity, and such a causal relationship is likely to also exist for respiratory morbidity and all-cause (non-accidental) respiratory- and cardiovascular-related mortality. Additionally, a causal relationship was found to be likely to exist between long-term exposure to ambient concentrations of PM<sub>2.5</sub> and cardiovascular morbidity, respiratory morbidity, and increased risk of mortality (ISA, 2008). Individuals particularly sensitive to PM<sub>2.5</sub> exposure include older adults, people with heart and lung disease, and children (PM implementation NFR 4-07).

Attainment of the PM<sub>2.5</sub> standards in the U.S. is estimated to lead to reductions in health impacts, including tens of thousands fewer premature deaths each year, thousands fewer hospital admissions and emergency room visits each year, hundreds of thousands fewer absences from work and school, and hundreds of thousands fewer respiratory illnesses in children annually. The EPA's evaluations of the science concluded that there was not sufficient information to either support or refute the existence of a threshold for health effects from PM exposure; i.e., emissions reductions resulting in reduced concentrations below the level of the standards may continue to provide additional health benefits to the local population (PM implementation NPR 11-05).

It is not clear what the precise role of BC is within the particulate mix in terms of health impacts. However, the U.S. EPA has determined that it is appropriate to control fine particles as a group, rather than singling out any individual component, because it was impossible to rule out any component within the mix as not contributing to the fine particle effects found in epidemiological studies (2006 Staff Report). Additionally, any measures that reduce BC are likely to also reduce other sources of PM. Further details on the EPA's findings can be found in the Appendix.

### 3. Sources of Black Carbon

Black carbon is generated due to incomplete combustion of fossil fuels or biomass. Large black carbon sources include diesel engines, domestic burning (eg, cookstoves), biomass burning, and industrial sources. Pollution control devices installed on power generation units in the industrialized world have, for the most part, been successful at reducing emissions from those sources. We describe a few of these sources in more detail here.

#### Shipping

Black carbon is produced by ships through the incomplete combustion of diesel fuel. International shipping is responsible for emitting between 71 and 160 Gg of BC annually (Corbett, Winebrake et al. 2007; Lack, Lerner et al. 2008), which is approximately 2% of total global BC emissions. This BC has the potential for significant impact on Arctic warming and melting, especially when emitted near or within the Arctic region. An estimated 85% of shipping emissions occur in the northern hemisphere (Corbett, Ship Emissions Assessment), but it is unclear what proportion of these emissions are transported to the Arctic.

The production of BC is dependent on engine type and combustion efficiency. A recent study found that the medium speed marine engines typically used on tugboats, fishing vessels and ferries emit BC at more than twice the rate of the slow speed engines used on large ocean-going ships (excepting containerhips) and the high speed engines used on passenger ships.<sup>2</sup> Historically, aerosol emissions from shipping have had a net cooling influence due to a high proportion of SO<sub>2</sub> emissions and a reduced effect for BC over low-albedo oceans (Fuglestedt, Berntsen et al. 2008). In the Fuglestedt study, shipping was estimated to be a source of 8.3 Tg of SO<sub>2</sub> but only 197 Gg of BC, and 61.3 Gg of OC. However, in the future clean air policies may lead to the use of lower sulfur fuel which could increase the net warming impact of emissions from shipping.

#### Oil and Gas Flaring

Quantifying BC emissions from flares is challenging. There are currently no existing practical approaches for quantifying the production of PM in plumes of flares or other open sources. Formation of PM from flares is extremely complex and dependent upon a number of factors including: the chemical composition of the fuel; turbulent mixing and the diffusion of air and fuel species; the rate of heat transfer of the flame and the residence time/temperature history through flame. Current research efforts focus on: studying the sooting propensity of binary fuel mixtures; directly measure soot emissions from flares in a controlled lab setting; measuring the optical properties of soot, which is necessary to support quantitative measurements; and developing a diagnostic to measure soot from flares in the field, to improve upon current qualitative descriptions of "opacity." A preliminary demonstration of field measurement technique shows promise for estimating soot flux in strongly sooting flares (personal communication, Johnson).

Using preliminary estimates of 177 ug/L of BC from burning natural gas, and an approximation of 32 MJ/m<sup>3</sup> natural gas, Klimont et al. estimated an emissions coefficient of 0.05 g/MJ. This emissions estimate can be combined with activity data from Elvidge et al. (2007). Twelve year

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<sup>2</sup> Although higher BC emissions were found in ships burning lower sulfur fuel, these ships had predominantly medium speed engines, and the engines rather than the fuel likely produced the higher BC emission rates. Lack, D. A., J. J. Corbett, et al. (2009). "Particulate emissions from commercial shipping: Chemical, physical, and optical properties." Journal of Geophysical Research-Atmospheres **114**.

record of national and global gas flaring volumes estimated using satellite data) to yield a very rough total of 288.2 Gg/year global BC emissions from flares. Both the activity and the emissions coefficients are very uncertain, and this number can be expected to change significantly in the future. Russia, the Former USSR, Africa, and the Middle East account for about 86% of the total emissions by this methodology, with the remainder of the emissions from other major oil and gas producing nations. Flaring sources in the North Sea nations are estimated to emit 4.1 Gg of BC, the rest of Europe about 3.1 Gg, Canada about 0.8 Gg, and the U.S. about 3.5 Gg BC (personal communication, Klimont).

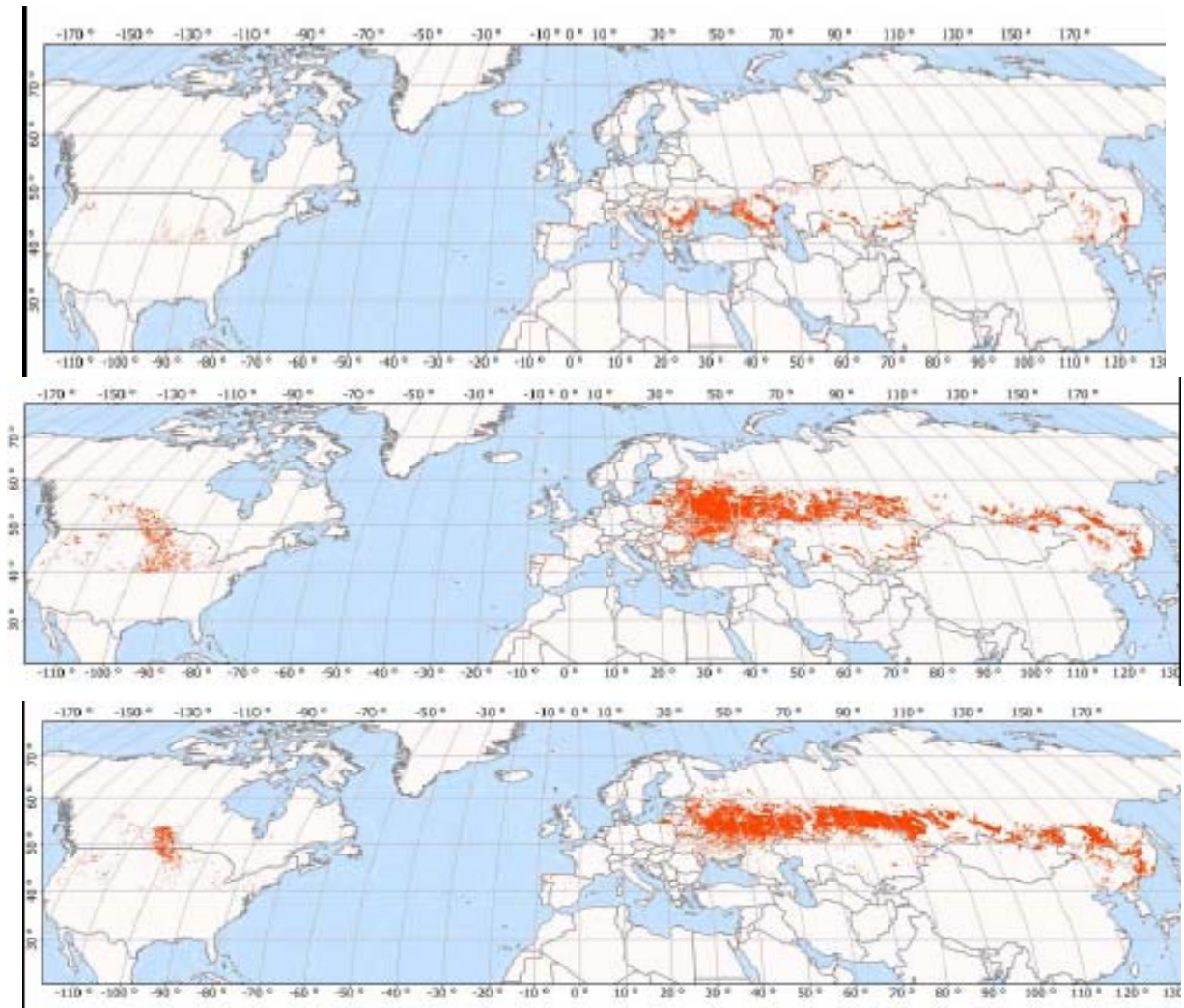
### Biomass Burning

Climate researchers have tended to focus on summer boreal forest fires as the principal source of BC emissions from seasonal biomass burning. Agricultural fires were not included in recent predictive models of how and when BC reached the Arctic because they are relatively small. However, recent Arctic field missions encountered plumes from agricultural burning in April and May 2008. The timing of these fires, in the spring rather than during the summer as was previously assumed, raises serious climate concerns because BC deposition in the Arctic has the greatest impact in the spring, the period of maximum BC-snow albedo feedback. In addition, the location of the burn plume with respect to clouds is important as warming from BC is enhanced over a reflective body.

The major sources of agricultural fires that affect the Arctic include: Eastern Europe/European Russia; Kazakhstan/Siberian Russia; Northeastern China; and North America (i.e. Canada + NE Great Plains, Minnesota). MODIS satellite data confirm fire activity in these regions over the past several years, with different regions showing peaks of burning at different times of year (Figure 4). North of 40° Europe/European Russia has the highest agricultural burning rate, followed by Central/NE Asia/Asiatic Russia. The rate of burning in North America is smaller, but still significant.

In Western Europe, agricultural fires have been banned since the 1980s because of air quality concerns. However in many Eastern European countries, burning continues despite an EU ban due to lack of enforcement. Burning practices may also be culturally entrenched. In the US and Canada agricultural fires are permitted under limited circumstances. In China, regulations on field burning exist but have been poorly enforced.

In Russia, the country with the highest percentage of BC emissions from biomass burning north of 40 degrees, addressing these emissions could be challenging. Since the fall of the Soviet Union in 1991, government management of wild and anthropogenic fires has declined (Shvidenko, 2003). At the same time, vegetation cover has increased in many rural areas. These institutional and land-use changes have led to higher frequency fires both in forest and steppe land.



**Figure 4** From, *MODIS Terra Global Land Cover and Burned Area, 1 km* for March, April, May 2006 fire burn locations on croplands north of 40 degrees. 2006 is considered to be a typical fire year.

## 4. Review of Emission Inventories and Uncertainties

### *Challenges in determining black carbon inventories*

Several global and regional inventories of BC have been published in the literature or developed by the collaborators involved in this report. A number of uncertainties are associated with these inventories. On a global scale “the total uncertainties are about a factor of 2” (Bond, Streets et al. 2004) though uncertainty may be greater or smaller for a specific source. Because emissions are dependent on the nature of the combustion process, “emissions can vary even among apparently similar technologies” (Bond, Streets et al. 2004) or for different kinds of use of a single combustion source (Roden, Bond et al. 2006; Roden, Bond et al. 2009). Different optical and thermal methods can yield EC or BC values that differ by up to a factor of 2 (Hitzenberger, Petzold et al. 2006). The term black carbon itself is occasionally confusing, as it is sometimes used differently between different researchers. Bond (2004) uses a definition that classifies BC as those particles that have an absorption efficiency of  $7 \text{ m}^2/\text{g}$  at 550 nm incident radiation. Some inventories use “elemental” carbon as a proxy for BC: this term specifically refers to the carbonaceous component that does not oxidize at low temperatures.

Because some BC sources also emit significant amounts of OC, which have reflective and therefore cooling properties, it is necessary to quantify the other species that are co-emitted by each source to determine the net benefits of BC mitigation. As with BC, OC quantification involves both uncertainties and nomenclature issues: some groups measure only the carbon mass of the aerosol that is not black, whereas others include the hydrogen and oxygen mass as well (usually referred to as “organic matter” or OM). According to Bond (2004), the mass of “organic matter” is the key determinant in determining effects on radiative forcing. Jacobson (2002) reports a typical ratio of 1.3:1 for OM:OC from fossil fuels, but others note that the ratio tends to increase with aging of OC particulates in the atmosphere. Secondary organic aerosol production is another complicating factor in determining OC inventories.

Additionally, different inventories use different size cutoffs. Bond et al. use  $1 \mu\text{m}$  because particles below that size contribute the majority of the radiative effects: however, studies derived from health-based data may use  $\text{PM}_{2.5}$  (typically yielding masses 10 to 15% higher than  $\text{PM}_{1.0}$ ) or even  $\text{PM}_{10}$  or bulk emissions (which may be 25 to 40% higher, especially for OC).

The inventories reported in this document generally use regional fuel-use data (from IEA or other sources) multiplied by emission factors specific to each technology and nation. However, top down techniques have also been used to estimate sectoral emissions contributions and sometimes reach different conclusions (Gustafsson, Krusa et al. 2009).

***Global Inventories*****Table 1 Global Sectoral Carbanaceous Emissions Inventory, Bond (2004),**

Emissions (Gg/year)	BC	OC	OC:BC Ratio
<b>Open burn:</b>			
Forest	1238	11239	9.1
Savanna	1715	12147	7.1
Crop residue	328	1567	4.8
<b>Contained combustion</b>			
Coal power	7	5	0.71
Diesel-on-road	792	292	0.37
Wood-residential	880	3506	4.0
Ag waste-residential	393	1492	3.8
Animal waste – resident.	208	750	3.6
Coal – industry	642	450	0.70
Diesel-residential	85	28	0.33
Coal-residential	480	422	0.88
Diesel-off-road	579	288	0.50
Gasoline-transport	125	904	7.2
Other	478	776	1.6
Total	7950	33866	4.3

In the Bond (2004) inventory (Table 1), there is a clear division between those sectors with OC:BC emissions ratios greater than 3 (i.e., various kinds of open and agricultural burning as well as gasoline transport emissions) and those sectors with emissions ratios less than 1 (i.e., diesel and coal burning). However, determination of net climate effects is not necessarily straightforward. Combustion of high sulfur content coal without end-of-pipe control technologies can lead to increased levels of sulfate particles in the atmosphere, which have a cooling effect; therefore, particulate control measures on these sources may not result in a net cooling effect. Residential wood burning efficiency measures may also reduce CO<sub>2</sub> and CH<sub>4</sub> emissions which will offset the higher OC:BC ratios. Diesel particulate traps may decrease fuel mileage leading to increased emissions. For northern springtime agricultural burning, OC that is transported over snow and ice is likely to be less effective as a cooling agent because of the high albedo of the underlying surface: Koch et al. (2007) even calculate a net positive forcing from the direct effect of European OM due to significant Arctic transport. In spite of these complications, the magnitudes and ratios in the above table enable a first pass determination of which sectors have significant potential for climate change mitigations.

***Arctic Nation Emissions***

Tami Bond has developed nation by nation breakdowns of the global inventories presented in Table 1. The inventories in

Table 2 show the distribution of BC emissions between nations, with the U.S. contributing more than 50% of the total emissions of the Arctic nations and Russian Federation contributing 60% of the remainder. Road transport emissions account for almost a third of the total BC emissions, and off-road transport accounts for another 20%. Open burning also contributes 20% of total BC emissions, but is accompanied by significant co-emissions of OC (Table 3). Therefore, mitigation measures targeting open burning sources are only likely to have significant cooling effects in regions that are snow covered.

**Table 2 Black carbon emissions (Gg/yr) by sector and nation for the Arctic Nations (Bond)**

	Canada	USA	Russian Fed	Iceland	Denmark	Norway	Sweden	Finland
Ag Burn	12.25	3.02	8.86	0	0	0	0	0
Industry	2.9	14.38	11.97	0.01	0.06	0.21	1.69	1.31
Open Burn	40.35	60.4	80.56	0	0.04	0.05	0.14	0.05
Power Gen.	0.19	2.82	1.26	0	0.02	0	0.01	0.02
Residential Biofuel	3.25	32.59	27.8	0.01	0.42	1.16	3.04	1.01
Residential Coal	0.27	19.88	12.25	0	0.06	0	0	0.03
Residential Other	0.53	3.21	0.56	0	0.06	0.04	0.12	0.07
Road Transport	17.07	211.33	29.78	0.09	2.99	2.4	4.6	3.25
Off-road transport	17.7	100.42	27.11	0.56	3.14	3.24	2.86	2.68
<b>Total</b>	<b>94.51</b>	<b>448.05</b>	<b>200.15</b>	<b>0.67</b>	<b>6.79</b>	<b>7.1</b>	<b>12.46</b>	<b>8.42</b>

**Table 3 Organic carbon emissions (Gg/year) by sector and nation for the Arctic Nations (Bond)**

	Canada	USA	Russian Fed	Iceland	Denmark	Norway	Sweden	Finland
Ag Burn	58.58	14.45	42.37	0	0	0	0	0
Industry	15.57	108.25	37.97	0	0.85	1.88	7.25	5.73
Open Burn	572.47	826.47	1136.71	0	0.07	0.31	1.24	0.35
Power Gen.	0.16	1.92	1.67	0	0.01	0	0.01	0.04
Residential Biofuel	17.98	180.2	166.35	0.05	2.42	6.69	17.63	5.88
Residential Coal	0.31	16.04	14.33	0	0.04	0	0	0.24
Residential Other	0.38	3.13	0.32	0	0.04	0.06	0.05	0.03
Road Transport	10.21	128.26	28.14	0.05	1.28	1.03	2.14	1.33
Off-road transport	9.86	68.98	12	0.19	2	1.46	2.28	1.49
<b>Total</b>	<b>686.52</b>	<b>1347.7</b>	<b>1439.86</b>	<b>0.29</b>	<b>6.71</b>	<b>11.43</b>	<b>30.6</b>	<b>15.09</b>

Cofala et al. (2007) provide a largely independent estimate (

Table 4) of contained emissions from these regions developed from the GAINS database, though some of the emission factors come either from Bond (2004) or from the same sources that Bond et al. used. For several European regions and Russia national rather than international data sources were used. These emissions are estimated for particles up to 2.5 microns (rather than just 1.0), which can lead to slightly larger emissions estimates. High emitting vehicles were not estimated separately for this work.

**Table 4: Black Carbon and Organic Carbon Emissions from Contained Sources in near-Arctic regions in the year 2000 (Cofala, 2007).**

Region	Sub-region	BC	OC	OC:BC
North America	Canada	33	36	1.11
	USA	247	318	1.28
	<b>Total North America</b>	<b>280</b>	<b>354</b>	<b>1.26</b>
Europe (excluding former USSR)	Eastern Europe <sup>3</sup>	99	183	1.85
	Western Europe	387	502	1.30
	<b>Total Europe</b>	<b>486</b>	<b>685</b>	<b>1.41</b>
Former USSR		<b>219</b>	<b>367</b>	<b>1.68</b>

There are various inventories at the 1x1 degree scale: eg, Cooke et al. (Cooke, Lioussé et al. 1999). Additionally, historical inventories at that scale have been developed, such as Ito and Penner (2005) and Junker and Lioussé (2008). While extremely important for climate models, these papers often do not report the sectoral level emissions estimates that are most useful for the purposes of this paper.

### *BC Emissions by Latitude*

The Arctic is more sensitive to black carbon that can be transported into the region. Absent computer modeling, latitudinal emissions distributions give an approximation of the capability of such transport. Table 5 shows the emissions from the Bond inventory by latitude. 19% of all black carbon emissions occur above 40° latitude (a common rule of thumb used for Arctic transport), and of those high latitude emissions, a third are transport related.

**Table 5 Black carbon emissions (Gg/yr) in 2000 by latitude and sector (Bond)**

Latitude	Power	Industry	Res fossil	Res bio	Transportation	Ag burning	Open burning
-85	0	0	0	0	0	0	0
-75	0	0	0	0	0.016	0	0
-65	0	0	0	0	0.069	0	0
-55	0.001	0.064	0.01	0.057	0.426	0.00276	0.001863
-45	0.012	0.834	0.379	0.773	3.58	0.21414	1.0024
-35	0.479	17.036	7.582	11.334	54.028	22.392	34.634
-25	0.724	28.26	17.385	28.451	87.332	12.652	114.08
-15	0.072	14.338	4.815	44.155	48.24	9.8214	595.08
-5	0.135	34.842	6.206	132.65	75.554	14.76	480.7
5	0.397	40.866	7.983	171.12	59.02	33.809	708.5
15	1.578	66.464	14.4	247.34	126.06	58.217	226.27
25	4.553	203.37	131.75	410.6	181.17	85.045	98.632
35	10.32	441.91	270.2	278.81	375.86	73.302	18.688
45	6.574	159.21	100.97	152.55	307.37	40.719	55.948
55	3.265	70.845	61.091	30.362	168.57	20.209	171.94
65	0.299	4.911	2.128	3.059	17.158	0.19171	74.455
75	0	0.01	0	0.004	2.136	0.00041	0.04053
85	0	0	0	0	0.008	3.00E-05	0

<sup>3</sup> Not including former USSR nations that are included in the Former USSR emissions estimate: e.g., Belarus, Estonia, Latvia, Lithuania, Moldavia, Ukraine, Armenia, Georgia, Kazakhstan, Kyrgyzstan.

***U.S. Inventories***

Three U.S. inventories of BC and two U.S. inventories of OC are shown here. The specific inventories examined included that of Streets et al. for the year 1996, Battye et al. for the year 2000, and the U.S. Environmental Protection Agency (EPA) for the year 2001. The Streets inventory was generated specifically for the purpose of producing global bottom-up (i.e., technology-based) BC and OC inventories. The Battye inventory was specifically for BC (and did not include OC), and was generated using PM<sub>2.5</sub> data from EPA's 1999 National Emissions Inventory (NEI) and BC speciation factors for that PM<sub>2.5</sub> data. The EPA inventories were for elemental carbon and primary organic aerosol, which we assume to be equal in mass to BC and OC.

Despite some disagreement between the inventories, it is clear that mobile sources (mainly diesel) contribute about half of all US BC emissions, and that the power sector is only a small relative source (due to efficient combustion and emissions control technologies).

**Table 6 United States BC inventories, circa 2000 (Gg).**

	<b>Biomass Burning</b>	<b>Residential/ Area</b>	<b>Industry/ Non-Power Point Sources</b>	<b>Mobile</b>	<b>Power</b>	<b>Other (non- combustion sources)</b>	<b>Total</b>
Streets <sup>a,b</sup>	61	79	66	203	6		415
Battye <sup>a</sup>	93	41	29	236	4	29	433
EPA	110	54	18	234	14	7	436

<sup>a</sup> Estimated "residential" emissions rather than "area" emissions. "Area" emissions include sources such as commercial charbroilers that are in many sites within a locality.

<sup>b</sup> Did not estimate emissions for non-combustion sources.

**Table 7 United States OC inventories, circa 2000 (Gg).**

	<b>Biomass Burning</b>	<b>Residential / Area</b>	<b>Industry/ Non-Power Point Sources</b>	<b>Mobile</b>	<b>Power</b>	<b>Other (non- combustio n sources)</b>	<b>Total</b>
Streets <sup>a,b</sup>	954	348	31	133	10		1,476
EPA	658	298	121	148	12	90	1,326

<sup>a</sup> Estimated "residential" emissions rather than "area" emissions. "Area" emissions include sources such as commercial charbroilers that are in many sites within a locality.

<sup>b</sup> Did not estimate emissions for non-combustion sources.

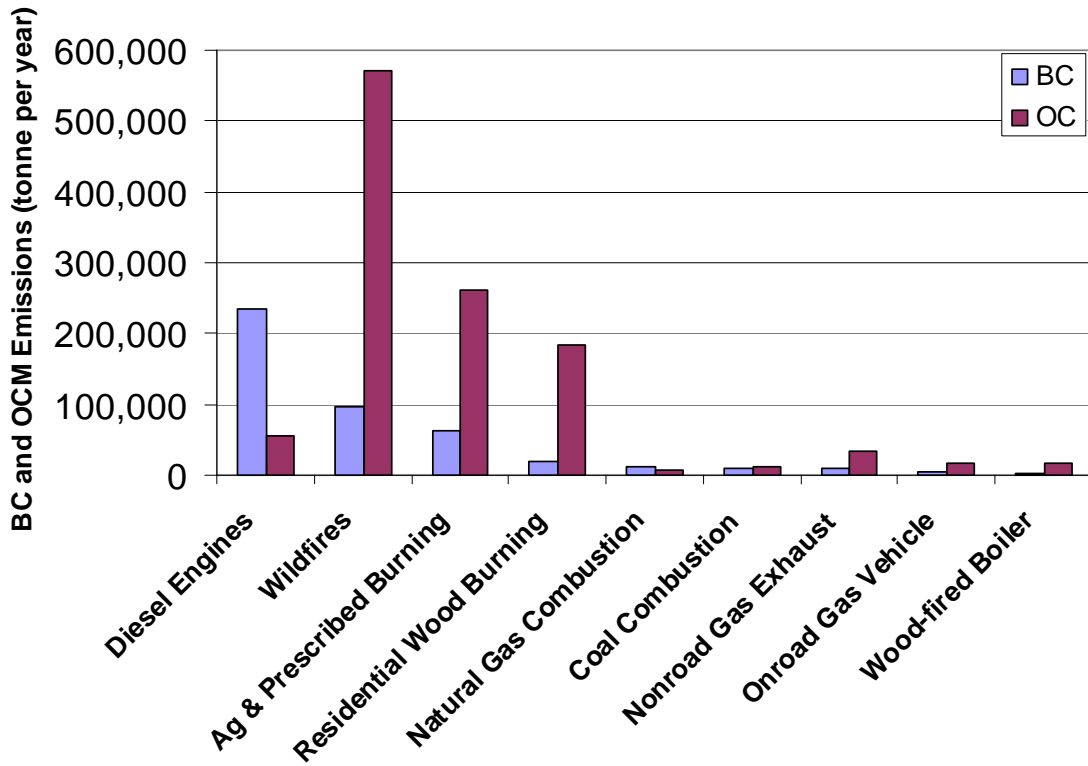


Figure 5 US BC and OC emissions by sector for 2002

For biomass burning in particular, data from WRAP(2007) and AirControlNET indicate that about 60% of  $PM_{2.5}$  emissions in the US result from wildfires (mainly in the western states), and the remainder of the  $PM_{2.5}$  emissions is split between agricultural fires (mainly in the southeastern states) and slash or prescribed burning (both in the southeastern and the western states).

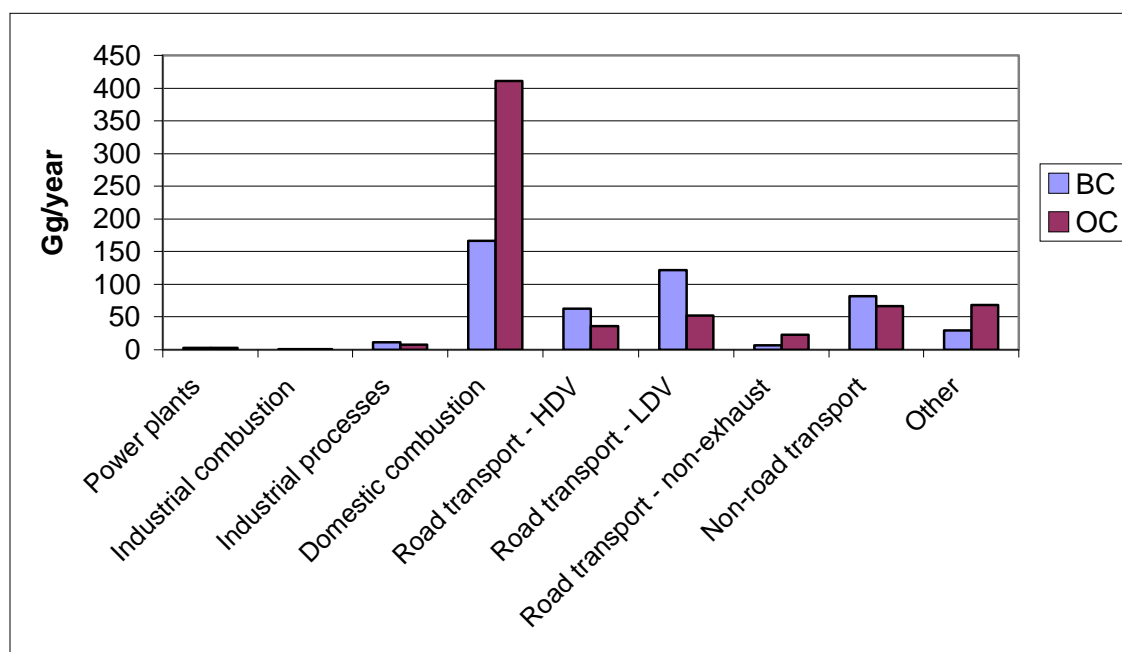
### *European and Asian Inventories*

A number of detailed regional inventories have been prepared by Klimont et al. (

Table 8). The emissions estimates for the “other” sector for the Former USSR include tentative estimates of carbonaceous emissions from oil and gas flaring amounting to 73 kt BC and 14 kt OC.

**Table 8 Black carbon and organic carbon emissions by region and sector, from Kupiainen and Klimont (2007) , Cofala (2007), and Klimont (2009).**

	Europe <sup>4</sup>		Former USSR <sup>5</sup>		China <sup>6</sup>	
	BC	OC	BC	OC	BC	OC
Power Plants	3	3	2	6	4	2
Industrial Combustion	1	1	1	3	254	268
Industrial Processes	11	8	25	20	67	47
Domestic combustion	166	411	91	188	775	2209
Road Transport – HDV	62	36	22	16	70	248
Road Transport – LDV	121	52	3	23		
Road Transport – non-exhaust	7	22	1	3		
Non-road transport	82	67	41	31	54	35
Other	29	69	103	93	120	395
<b>TOTAL</b>	<b>483</b>	<b>668</b>	<b>290</b>	<b>382</b>	<b>1345</b>	<b>3205</b>



**Figure 6 Emissions of BC and OC for Europe in 2000 after Kupiainen and Klimont (2007) - Atmospheric Environment**

<sup>4</sup> Emissions do not include forest fires, but include emissions from agricultural open burning where data was available. Kupiainen and Klimont (2007)

<sup>5</sup> The emissions originate from Kupiainen and Klimont (2007) and from Cofala et al. (2007). New flaring estimates included in “other” (see text).

<sup>6</sup> Emissions of BC and OC for China in 2000 as calculated in the GAINS model, Klimont et al. (2009) - Tellus

## 5. Projected emissions by Sector and Country

Emission projections are necessary in order to determine the changing magnitude of BC climatic effects over time and to identify where additional mitigation measures can make a difference. Making projections requires an evaluation of the effect of current and forthcoming air quality policies that target PM which in turn can significantly affect BC and OC emissions from new diesel vehicles and other particulate sources. Emission projections also need to account for changes in sectoral activities, technologies, economic conditions and population.

### *Global projected emissions*

Streets (2004) transformed the Bond (2004) inventories to the IPCC world regions, and then extrapolated out to 2050 for four different IPCC scenarios (of which only the A1B scenario results are shown here). These projections include assumptions about technology shift in developing countries towards the technology mix in the developed world, as well as technology advancement in the developed world itself. In the absence of this technology shift and advancement, there would be a 56% increase in BC emissions by 2030 under the A1B scenario. Streets also projects that residential biofuel elimination, industrial modernization, retirement of all superemitting vehicles, and a ban on open burning of crop residues could reduce emissions 30% from the 2030 projection.

**Table 9 BC and OC projections for selected regions and the world from Streets (2004)**

<b>BC</b>	<b>1996</b>	<b>2030A1B</b>	<b>2050A1B</b>
Canada	93	85	80
United States	414	308	225
OECD Europe	392	250	174
Eastern Europe	137	141	85
Former USSR	282	306	273
World	8035	7113	6082
<b>OC</b>	<b>1996</b>	<b>2030A1B</b>	<b>2050A1B</b>
Canada	772	808	743
United States	1476	1390	1140
OECD Europe	1032	840	752
Eastern Europe	310	244	213
Former USSR	1629	1617	1436
Global	34305	28737	28103

The projections in Table 10 include Current Legislation (CLE) scenarios that assume implementation of the already decided emission control legislation in each country, based on the current (end of 2003) national expectations of economic development. An alternative scenario (MFR) explores the emission reductions that could be achieved, for the same assumptions on the economic development, with the most advanced emission control technologies implemented in the GAINS model. The GAINS scenarios from December 2008 follow the same principles as Cofala et al (2007) but make use of the more recent information on legislation and projections of activity data. The national projections of future activities that have been collected for this study reflect expectations of national governments and thereby, in many cases, probably merely policy ambitions rather than the most likely developments; the impacts of the recent economic downturn and not included in any way. In the MFR case, large reduction potentials are indicated in all

regions. It must be stressed, however, that this scenario is very optimistic in terms of implementation of measures. Especially in the domestic sector, dominating emissions of carbonaceous aerosols, the data on age of installations, their lifetimes, etc. are of poor quality for most countries. These have to be seen as the lowest achievable levels, with current energy structures, when costs of implementation that would need to include preliminary scraping, is not considered as a constraint. More work is needed to validate a number of assumptions and work is in progress to develop a more realistic (constrained) MFR scenario.

The assessment includes preliminary estimates of flaring emissions, but does not include emissions from international shipping, aviation, and open burning of biomass with exception of field burning of agricultural residues for which estimates relied on the national reports.

**Table 10 More recent projections of BC emissions to 2030 from the GAINS model**

		Current Legislation		Maximum Feasible Reduction	
BC:	2000	2020	2030	2020	2030
North America	293	198	180	132	79
Western Europe	396	200	157	79	51
Central/Eastern Europe	90	83	80	18	14
Russia and NIS	280	351	365	206	190
		Current Legislation		Maximum Feasible Reduction	
OC:	2000	2020	2030	2020	2030
North America	389	284	250	158	119
Western Europe	436	240	197	104	90
Central/Eastern Europe	129	119	113	26	24
Russia and NIS	336	395	413	163	139

Shindell et al. included three different BC projections following the A1B storyline, one of which had global emissions decreasing monotonically, one of which had monotonically increasing emissions, and the third which had emissions increase to 2030, and then decrease again to near 2000 levels by 2050. This discrepancy between model projections demonstrates the IPCC statement (WGI Ch. 10) that future projections of forcing by BC and OC have been quite dependent on the model and emissions assumptions. Similarly, a CCSP Synthesis and Assessment Product (2008) concluded that one of the most important uncertainties in characterizing the potential climate impact of aerosols is the projection of their future emissions.

### ***Projections of BC from shipping***

As sea ice melts, more sea lanes open up, encouraging more shipping through the region. Although shipping emissions of BC in the Arctic region are relatively small at present, some estimates project they will increase by 2-3 times the global rate between now and 2050. The IPCC Fourth Assessment Report (Anisimov and et al. 2007) includes one study that suggests that by 2050, the Northern Sea Route will have 125 days per year with less than 75% sea-ice cover. These conditions would be favorable conditions for navigation by ice-strengthened cargo ships.

### ***U.S. Air Quality Policies in the Baseline***

Fine particulate matter (PM<sub>2.5</sub>) is regulated by air quality standards because of the health risk it poses [See: “Health Effects of Particulate and Black Carbon Emissions”, below]. BC and OC are components of PM<sub>2.5</sub>; therefore, regulations aimed at reducing PM<sub>2.5</sub> emissions will have an impact on BC and OC emissions as well. This section identifies and describes selected regulations that will come into effect between 2000 and 2020, and qualitatively expresses their general effect on PM<sub>2.5</sub>, BC, and OC. This review of policies serves to define the baseline for future projections, and also to provide possible templates for policies in other regions.

Clean Air Nonroad Diesel Rule. This rule regulates sulfur content, nitrogen oxides (NO<sub>x</sub>), non-methane hydrocarbons (NMHC), and PM emissions for nonroad diesels. Tier 4 standards will be phased in over the period from 2008 to 2015. At the time of signing (2004), average in-use sulfur content was approximately 3,000 ppm. Sulfur-sensitive control technologies necessary to meet the Tier 4 emission limits—such as catalytic particulate filters and NO<sub>x</sub> absorbers—required reductions in sulfur content in nonroad diesel fuels. The limit is 500 ppm for nonroad, locomotive, and marine diesel fuels. The limit will be further reduced to 15 ppm (ultralow sulfur diesel) effective June 2010 for nonroad fuel, and June 2012 for locomotive and marine fuels. Tier 4 standards contain a PM limit of 0.03 grams per brake horsepower-hour or less depending on the engine type. Projections estimate that this rule will save 129,000 tons of PM by 2030 at an annual cost of about \$2 billion (<http://www.epa.gov/nonroad-diesel/2004fr/420f04037.htm>).

Clean Air Highway Diesel Rule (or 2007 Highway Rule). This rule requires the sulfur content of highway diesel vehicles to be lowered from 500 ppm to 15 ppm. The rule contains a PM limit of 0.01 grams per brake horsepower-hour for new heavy-duty engines.

PM<sub>2.5</sub> NAAQS. In September 2006, EPA revised the daily PM<sub>2.5</sub> National Ambient Air Quality Standards (NAAQS) from 65 to 35 µg/m<sup>3</sup>, while retaining the yearly standard of 15 µg/m<sup>3</sup>. It is expected that the diesel rules and the Clean Air Interstate Rule will play a significant role in helping most areas of the United States comply with the revised PM<sub>2.5</sub> NAAQS. However, there will still be some localities in non-attainment for the revised PM<sub>2.5</sub> NAAQS. In the PM<sub>2.5</sub> NAAQS regulatory impact analysis, EPA identified various measures that could be used to bring localities into attainment with these revised NAAQS. These measures produced reductions in BC and OC, as well as PM<sub>2.5</sub>. However, because these measures are implemented locally, they are not expected to produce large reductions in nationwide emissions of BC and OC. Additionally, only 5% of the PM reductions are expected to be from elemental carbon (<http://www.epa.gov/ttnecas1/regdata/RIAs/Chapter%205--Benefits.pdf>).

Proposed NESHAP Rule for Reciprocating Internal Combustion Engines. The proposed NESHAP (National Emission Standards for Hazardous Air Pollutants) rule uses formaldehyde and CO as surrogates for hazardous air pollutants, but the rule is expected to reduce PM emissions as well. It does not directly address BC, and while the current abatement requirements are set a level achievable by retrofitting with oxidation catalysts the proposed rule includes a discussion of the possibility of setting standards that would require reductions at the level reached by particulate filters. EPA will be requesting comment on the desirability and feasibility of such a requirement. ULSD fuel will be required for non-emergency diesel engines of greater than 300 hp. Non-emergency diesels contribute about 5 Gg of BC a year, more than half of which comes from engines >300 hp built before 1996. (<http://www.epa.gov/ttn/atw/rice/fr05mr09.pdf>) Note that NSPS standards since July of 2006 require DPF on compression-ignition stationary internal combustion engines. (<http://epa.gov/ttn/atw/nsps/cinsps/fr11jy06.pdf>)

National Clean Diesel Campaign and Stimulus Funding. The National Clean Diesel Campaign provides grants and loans to state and local governments for retrofit projects that reduce diesel emissions from the existing fleet, including emissions of black carbon. In 2008, the program

received \$49.2 million in funding plus \$9.8 million for the South Coast and San Joaquin Valley. For 2009, funding has increased to \$75 million, including \$15 million specifically directed at the South Coast and San Joaquin Valley. Further, the new economic stimulus bill has allocated an additional \$300 million to the NCDC. These additional investments in retrofits should yield black carbon emissions reductions.

Proposed Marine Emission Control Areas. The U.S. and Canada have submitted a proposal to the IMO requesting that an Emission Control Area be designated within 200 nautical miles (230 miles?) of the Canadian and U.S. coastlines. The ECA would not take effect until at least 2012. The regulation would require fuel sulfur content of less than 10,000 parts per million (ppm) in the first phase of implementation, and then meet a 1,000 ppm limit in 2015. Ships built after 2016 for use in the ECA would be required to meet Tier III NO<sub>x</sub> standards. Reductions of PM<sub>2.5</sub> are projected to reach 85000 tons annually by 2020, or about 74% of projected total marine emissions within 200 nm of U.S. and Canadian coasts for that year. The proposal does not include the U.S. and Canadian Arctic: the document states that further information will be gathered to address the necessity of controls in the Arctic marine regions.  
[http://www.eenews.net/features/documents/2009/03/30/document\\_pm\\_01.pdf](http://www.eenews.net/features/documents/2009/03/30/document_pm_01.pdf)

Smoke Management Programs. Some U.S. states have smoke management and other agricultural burning control programs in order to mitigate deterioration of air quality and other potential negative impacts of smoke intrusion.  
[http://www.wrapair.org/forums/fejfd/documents/task2/ag\\_surv\\_rpt.pdf](http://www.wrapair.org/forums/fejfd/documents/task2/ag_surv_rpt.pdf)

Other sectors. In addition to the work on diesel engines, EPA is investigating options for reducing black carbon emissions from other sectors, both domestically and internationally.

**Table 11 Summary of recent U.S. Transport Policy PM Limits**

		PM Limits (g/bhp-hr)
U.S. Heavy Duty Highway Engines	1984	0.60
	1991-93	0.25/0.1 <sup>a</sup>
	1994-97	0.1/0.07 <sup>a</sup>
	1998-2006	0.1/0.05 <sup>a</sup>
	2007+	0.01 <sup>b</sup>
	EU, 1998 (this source)	0.11
Non-road, >175 hp	1996-2001	0.4
	2006+	0.15
Non-road	Tier 4, 2011-2015	0.03 <sup>c</sup>
U.S. Locomotive Regulations	1973-1999 (Tier 0)	0.6/0.72/0.26 <sup>d</sup> /0.22 <sup>d</sup>
	2000-2004 (Tier I)	0.45/0.54/0.26 <sup>d</sup> /0.22 <sup>d</sup>
	2005+ (Tier II)	0.20/0.24/0.13 <sup>d</sup> /0.1 <sup>d</sup>
	2011/2012 Tier 3	0.1 <sup>d</sup>
	2013 Tier 4	0.03 <sup>d</sup>

Most data: <http://www.epa.gov/otaq/cert/hd-cert/stds-eng.pdf>

**a)** Some vehicles (eg, urban buses) had tighter PM constraints, **b)** Clean Air Highway Diesel Rule, **c)** Clean Air Nonroad Diesel Rule: <http://www.epa.gov/nonroad-diesel/2004fr/420f04032.htm#standards>; applies to >25 hp, .01 for most engines, **d)** New locomotive rule: Remanufactured Tier 0 + 1 engines required by 2010, Remanufactured Tier 2 engine required by 2013. Slightly different requirements for switch vs. line-haul & passenger locomotives for remanufactured engines. (Draft Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression-Ignition Engines Less than 30 Liters per Cylinder) <http://www.epa.gov/otaq/regs/nonroad/420r08001a.pdf>

For comparison, a short summary of the current EU PM limits is shown in Table 12.

**Table 12 Summary of recent EU Transport Policy PM Limits**

		PM Limits	PM Limits, g/bhp-hr
Europe, passenger vehicles + light commercial < 1305 kg. Euro 5 + 6 standards hold for up to 3500 kg: all units in g/km <sup>7</sup>	Euro 5 – 2009	0.005	See note
	Euro 6 - 2014	0.005	See note
Europe, Heavy duty diesel + large goods vehicles <sup>a</sup> (g/KWh)	Euro V – 2008	0.02	.015

<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF>

a: Numbers listed for large goods vehicles: HD diesels limits and dates are very similar.

### *U.S. Emissions Projections in the Baseline*

EPA developed six inventory projections for PM<sub>2.5</sub>, BC, and OC as part of the NAAQS RIA, designated A through F. These projections are based in large part on the policies detailed above. This paper deals with scenarios A, C, and F only. Scenario A represents the emission inventory in 2001. Scenario C represents the emission projections for 2020, taking into account such national regulations as the Clean Air Nonroad Diesel Rule, the Clean Air Highway Diesel Rule, the Clean Air Interstate Rule, and others. When the emission inventory for Scenario C was modeled to determine resultant PM<sub>2.5</sub> ambient air concentrations, some localities were found to be above the NAAQS limits of 15 µg/m<sup>3</sup> as an annual average, and 35 µg/m<sup>3</sup> as a 24-hour average. Therefore, additional local measures to further reduce emissions were considered for those localities, until those localities came into compliance with the 15/35 µg/m<sup>3</sup> ambient concentration limits. The resultant emissions scenario was labeled Scenario F.

Table 13 shows EPA estimates for BC and OC for the years 2001, 2015, and 2020. The estimates for the year 2020 are for Scenario C (U.S. federal regulations implemented, but some local areas still in non-attainment for the PM<sub>2.5</sub> NAAQS) and Scenario F (local measures implemented such that all localities in the United States are in PM<sub>2.5</sub> attainment). The impacts of the local measures from Scenario C to Scenario F are limited, with reductions of approximately 6 percent and 2 percent for BC and OC, respectively.

Table 13 also indicates that U.S. BC emissions are projected to decline from 436 Gg in 2001 to 255 Gg in 2020 Scenario F; this represents a reduction of approximately 42%. In contrast, OC emissions are projected to decline from 1,326 Gg in 2001 to 1,206 Gg in 2020 Scenario F; this represents a reduction of 9%. BC emissions reductions represent 60% of the total organic particle reductions, consistent with BC being about 60% of diesel PM emissions. Mobile source BC emissions are estimated at 234 Gg in 2001, representing 54% of the nationwide BC emissions of 436 Gg. Under 2020 Scenario F, mobile source BC emissions are projected to decline to 71 Gg, a reduction of 163 Gg. In fact, because the total reduction of BC emissions from all sources from

<sup>7</sup> The conversion between hp and kW is 1 hp = 0.746 kW. Some g/km to g/bhp-hr conversion factors are listed on pg. 111 of <http://www.epa.gov/otaq/regs/hd-hwy/2000frm/r00010.pdf> - for light heavy duty engines multiply by 1.23 to go from g/bhp-hr to g/mi. Typically, about 60% of PM emissions from diesel vehicles are black carbon: however, this ratio will change depending on the control technology.

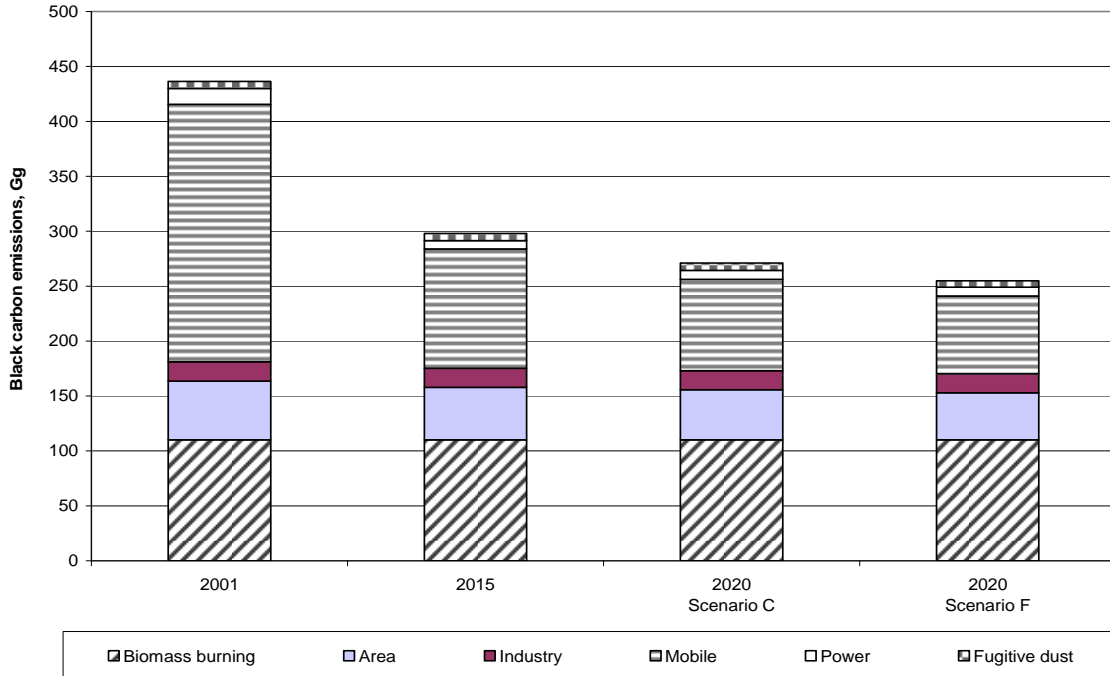
2001 to 2020 Scenario F is 181 Gg, the reduction of 163 Gg from mobile sources represents approximately 90% of the nationwide BC reduction.

**Table 13 United States BC and OC inventories for 2001, 2015, and 2020 (Gg).**

Sources	EPA Inventories, from PM <sub>2.5</sub> NAAQS Regulatory Impact Assessment			
	2001	2015	2020 Scenario C <sup>a</sup>	2020 Scenario F <sup>b</sup>
<b>BC</b>				
Mobile	234	109	83	71
Fugitive dust	7	7	7	6
Area	54	48	46	43
Industry	18	17	17	17
Power	14	8	8	8
Biomass burning	110	110	110	110
Total	436	298	271	255
<b>OC</b>				
Mobile	148	104	87	85
Fugitive dust	90	90	90	89
Area	298	267	256	241
Industry	121	118	118	116
Power	12	18	21	21
Biomass burning	657	657	657	655
Total	1,326	1,256	1,230	1,206

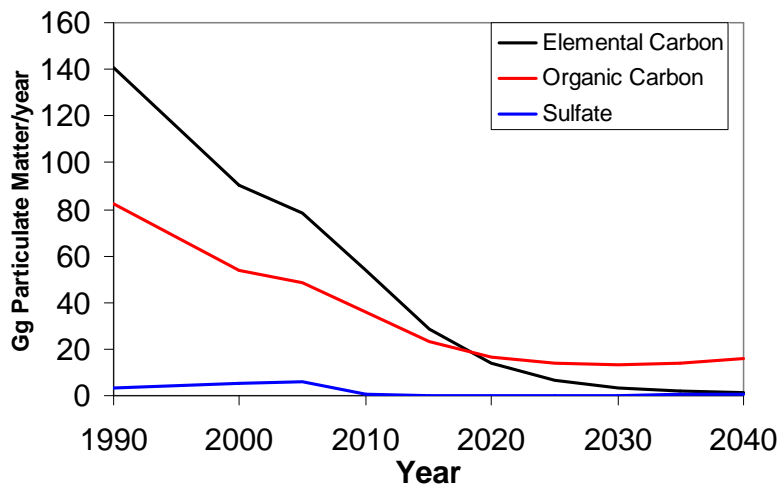
<sup>a</sup> Scenario C: Base case projection with Clean Air Visibility Rule, Clean Air Mercury Rule, Clean Air Visibility Rule.

<sup>b</sup> Scenario F: Compliance with PM<sub>2.5</sub> NAAQS: 15 µg/m<sup>3</sup> annual average, 35 µg/m<sup>3</sup> 24-hour average.



**Figure 7 Projections of U.S. black carbon policies to 2020 given current policies.**

More detailed projections of PM and BC emissions from the diesel vehicle fleet have been extracted from the new EPA draft MOVES emissions modeling system (<http://www.epa.gov/otaq/models/moves/index.htm>), using data points every 5 years. Figure 8 shows projected emissions of elemental carbon, organic carbon, and sulfates from all diesel vehicles from 1990 to 2040, clearly showing the large reductions due to current regulations. Figure 9 shows projected emissions of elemental carbon from 2000 to 2040 by vehicle class for the seven largest emission source types in 2000, leaving out the smaller sources from passenger cars, transit buses, refuse trucks, single unit long-haul trucks, and motor homes. Figure 10 shows projected emissions of elemental carbon in 2010 by vehicle type and model year.



**Figure 8 Projected U.S. Diesel Fleet Emissions by species for PM<sub>2.5</sub> generated from the draft MOVES model**

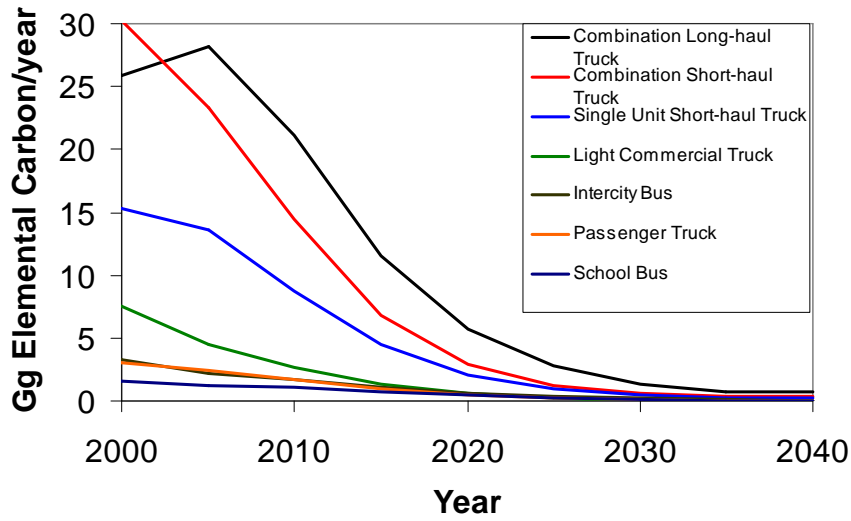


Figure 9 Projected U.S. Diesel Fleet Emissions of Elemental Carbon by vehicle type generated from the draft MOVES model

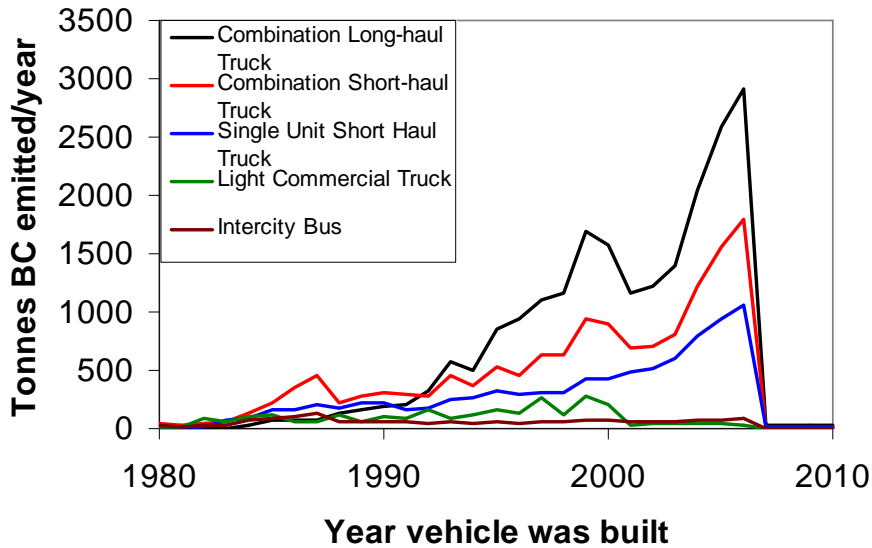


Figure 10 Tonnes of BC emitted in 2010 by vehicle type and model year generated from the draft MOVES model

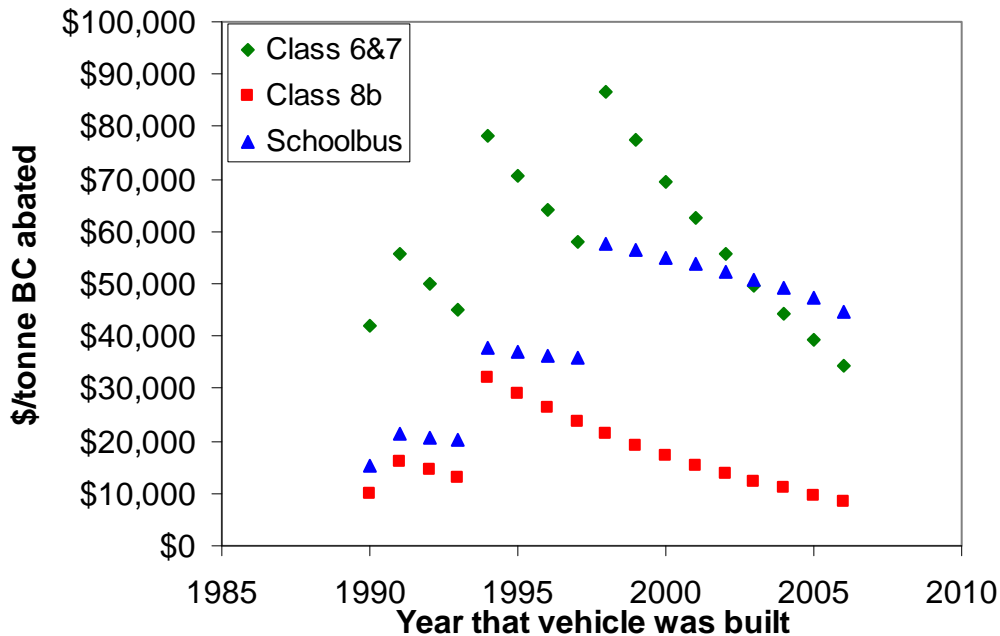
## 6. Mitigation Options and Costs

### *Diesel Transport Abatement Options*

Catalyzed Diesel Particulate Filters (CDPF):

*Diesel particulate filter* means an emission control technology that reduces PM emissions by trapping the particles in a flow filter substrate and periodically removes the collected particles by either physical action or by oxidizing (burning off) the particles in a process called regeneration. (<http://epa.gov/ttn/atw/nsps/cinsps/fr11jy06.pdf>).

The cost of a CDPF retrofit, including economies of scale, is estimated to be \$2500 for a Class 6 or 7 truck or a school bus, and \$4300 for a class 8b truck, of which a quarter is due to retrofit installation and labor rather than the filter itself. PM reductions per vehicle depended on the age of the vehicle, with older vehicles being more polluting but with a shorter expected lifetime post-retrofit. Figure 11 shows this graphically: for each vehicle category, all else equal, older vehicles are less cost-effective to retrofit than newer vehicles because of shorter lifetime. However, in 1991, 1994, and 1998 new regulations were passed, such that all vehicles built after those dates are less polluting than vehicles built before those dates. These reductions range from 0.04 to 0.24 lifetime tons of PM for the class 6, 7, and school bus category, and 0.11 to 0.43 lifetime tons of PM for class 8b vehicles. If BC is about 75% of PM emissions from diesel engines, this gives a cost/ton of BC reduction ranging from \$9000/ton to \$80,000/ton depending on the vehicle year and class being retrofitted. Retrofitting certain high emitting vehicles may be more cost efficient than the fleet average.



**Figure 11 Abatement cost in 2007 by vehicle class and model year. Discontinuities are visible where newer model years have tighter standards and therefore less economical mitigation opportunities.**

Note that the EPA analysis found that CDPF retrofits were not compatible with many bulldozers, and therefore did not analyze CDPF retrofit costs for any nonroad vehicles.

<http://www.epa.gov/cleandiesel/documents/420s06002.pdf>. A list of specific retrofit technologies can be found here: <http://www.epa.gov/otaq/retrofit/verif-list.htm>.

Diesel Oxidation Catalysts (DOC):

Diesel oxidation catalysts reduce about 20% of total PM emissions from a diesel vehicle, but result in very little BC reduction. While an individual DOC retrofit is about 20% of the cost of a CDPF retrofit, the DOC retrofit is only a little less expensive per ton of PM reduced because the DOC reduces only a little more than 20% as much PM as does a CDPF.

Other Abatement Options:

In addition to retrofit technologies, it is also possible to reduce emissions by reducing diesel engine use. This can happen in a number of ways. Reduction of idling through regulation, education, electrification of rest stops, and other means has been explored by the EPA: <http://www.epa.gov/ne/eco/diesel/idling.html>. Improved inspection and maintenance, improved efficiency, smart transport algorithms to plan shipping routes, shifting transport modes to rails, and other options can also lead to decreased emissions.

***Marginal Abatement Curves for U.S. diesel black carbon reductions***

More than 11 million diesel engines in America lack the latest diesel control technologies. Using the draft MOVES model from the EPA, elemental carbon emissions in the year 2010 were calculated for all vehicles by model year from 1990 to 2006. Using the EPA costs estimates for BC reductions for those vehicles, a marginal abatement cost curve was calculated for CDPF retrofits in 2010. The calculations show that particulate filter retrofits of the pre-2007 U.S. diesel fleet could yield, by themselves, about 130,000 tons of BC reduction over the lifetime of the vehicles for less than \$15,000 dollars per ton BC (or about \$2 billion total expenditure to retrofit more than half a million vehicles), of which about 19,000 tons of BC would be reduced in the first year after the retrofits.

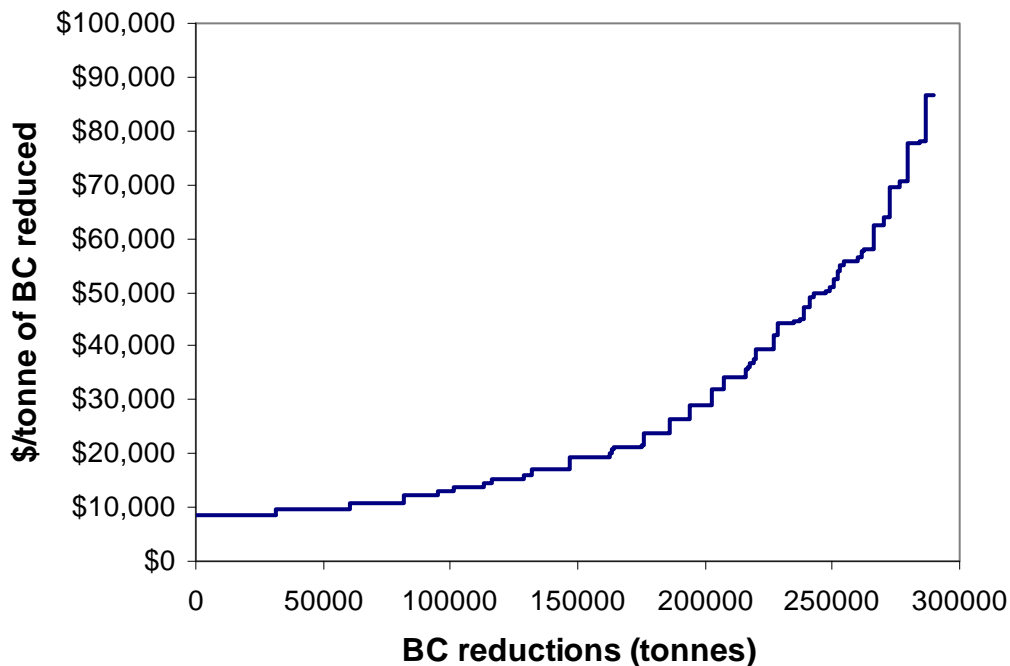
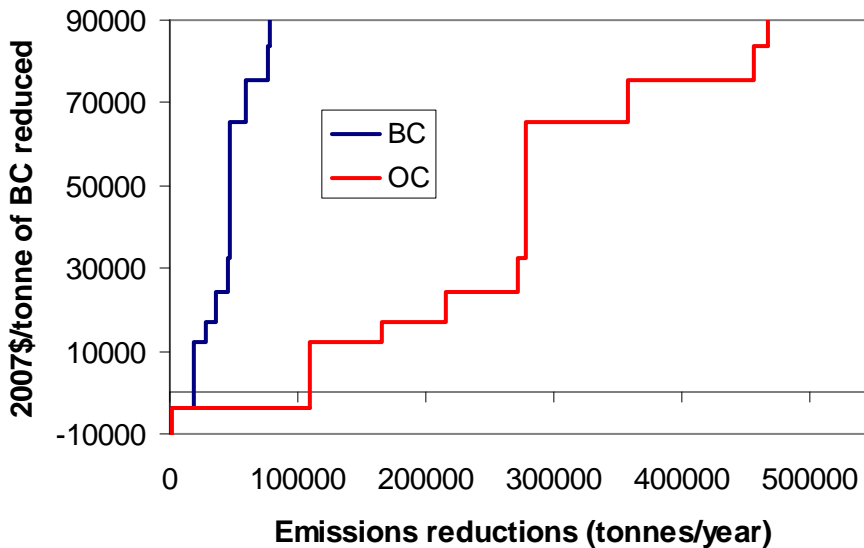


Figure 12 Marginal Abatement Cost for Lifetime BC Reduction from U.S. Diesel Fleet CDPF Retrofits in 2010 generated by combining MOVES model data with data from Figure 11.

***Marginal Abatement Curves for U.S. Biomass Burning Abatement Options***

There do exist a number of biomass burning mitigation options, though these are perhaps more speculative in nature than the control technologies available for contained combustion sources. The following chart shows marginal abatement costs for a number of biomass burning mitigation options. Stacking crop residues in bales and using propane burners, or using “backing fires” both help ensure more complete combustion and less smoldering that might lead to high particulate production (Ottmar 2001). The other option is to reduce burning by taking advantage of conservation tillage, soil incorporation, or hauling the crop residues to central processing sites. In addition, there are some forestry prescribed-burn mitigation options including timing of burns (directly before precipitation) or other moisture enhancing measures, pile burning to increase burn efficiency, or mechanical removal of material.



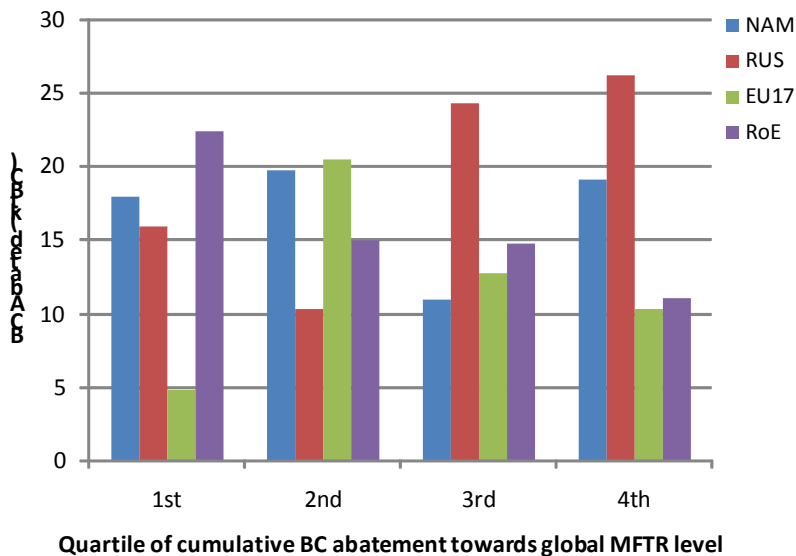
**Figure 13 U.S. agricultural/biomass burning marginal abatement cost curve for 2020.**

***Global and Regional Abatement Assessment***

Rypdal et al. (2009) assess future abatement strategies of particulate matter in terms of how much they reduce the climate impact of black carbon (BC) and organic carbon (OC) from contained combustion. The climate effect of BC will be different in different regions of the world due to differences in climate, radiation properties and deposition pathways. As a result region specific GWP values were developed for 12 different regions: EU17, Rest of Europe (RoE), Russia (RUS), North America (NAM), Latin America (LAM), East Asia (EAS), Centrally Planned Asia (CPA), South Asia (SAS), Japan (JPN), the Pacific OECD (POE), Africe (AFR) and the Middle East (MIDE). These GWP estimates range from 700 to 1320 for BC, including the indirect albedo effect, and from 0 to -82 for OC. The regions also represent different levels of economic development, status of implementation of air quality policies and costs for further abatement.

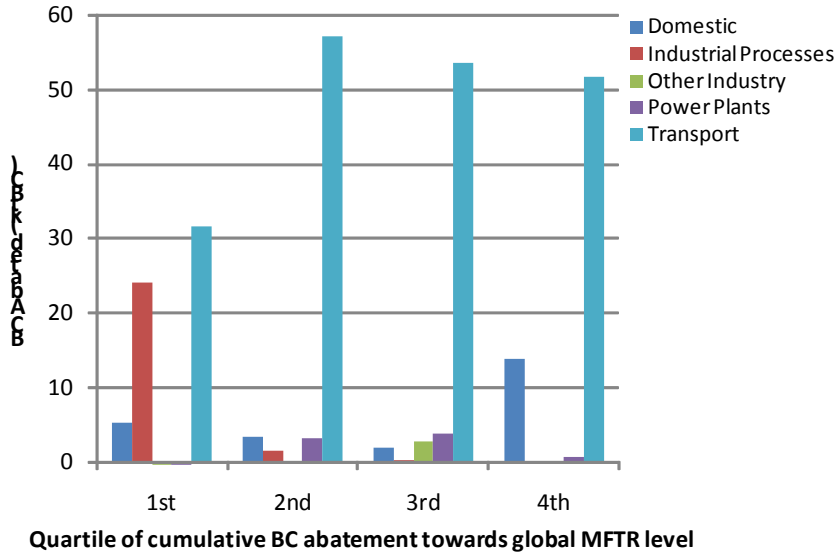
Emissions data originate from the global assessment of Cofala et al. (2007)<sup>8</sup>, and the estimates were prepared with the RAINS model. The baseline emission scenario (CLE: current legislation) for 2030 assumes implementation of the current national and international air pollution legislation in country specific reduction strategies. The maximum feasible technical reduction of emissions (MFTR scenario) illustrates a further technical potential for reductions in all regions, primarily via end-of-pipe and retrofitting measures. Fuel switching is not considered, so the MFTR relates to a given fuel mix. A given reduction in RF is obtained by reducing emissions from the CLE to the MFTR emission level following a marginal abatement cost (MAC) curve. A detailed MAC curve has been developed for each of the 12 regions to describe the technical abatement steps and costs of reducing BC (and co-emitted OC). The MAC curves for Europe were generated by the RAINS model, while extrapolations were made for the other regions due to lack of detailed region-specific data on technology availability and costs. More details can be found in Rypdal et al. (2009).

The histogram in Figure 16 illustrates which sectors have the largest potential for abatement, and we can see that the overall global abatement is dominated by transport abatement options. However, these are not the cheapest choices, and thus the first quartile is dominated by abatement in industrial process activities. For the near-Arctic regions (Figure 15) there are similar quantities of transport and industrial process abatement opportunities available, with transport still dominated the total maximum feasible reduction potential.

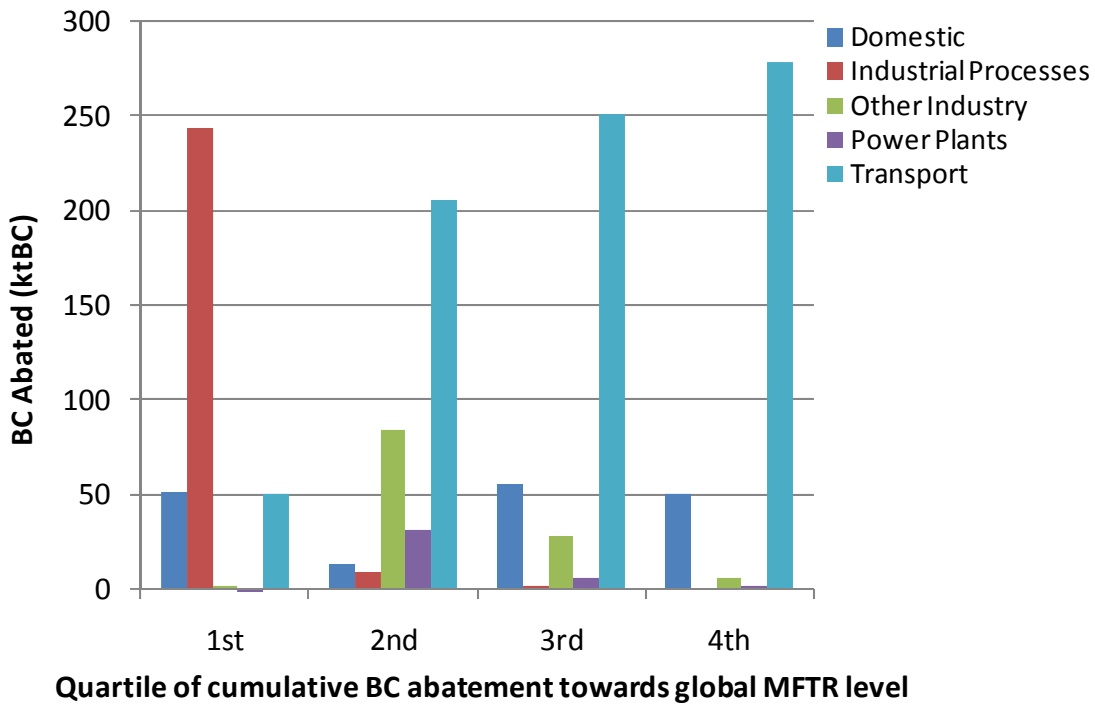


**Figure 14** Abatement contribution (in kt BC) from each region towards each quartile of the BC MAC curve for the near-Arctic regions to MFTR level. Ordered by cost, the abatement options in the 1<sup>st</sup> Quartile are cheaper than those in the 2<sup>nd</sup>, and so on (derived from Rypdal et al., 2009).

<sup>8</sup> Cofala, J., Amann, M., Klimont, Z., Kupiainen, K. and Höglund-Isaksson, L. 2007. Scenarios of global anthropogenic emissions of air pollutants and methane until 2030. *Atmos. Environ.* 41/38, 8486-8499.



**Figure 15** Abatement contribution (in kt BC) from each sector towards each quartile of the BC MAC curve for the near-Arctic regions to MFTR level. Ordered by cost, the abatement options in the 1<sup>st</sup> Quartile are cheaper than those in the 2<sup>nd</sup>, and so on (derived from Rypdal et al., 2009).



**Figure 16** Abatement contribution (in kt BC) from each sector towards each quartile of global BC MAC curve to MFTR level. Ordered by cost, the abatement options in the 1<sup>st</sup> Quartile are cheaper than those in the 2<sup>nd</sup>, and so on (Rypdal et al., 2009).

Three different mitigation scenarios are developed to explore the different roads for abating black carbon emissions (and co-emitted OC). In scenario 1, emission reductions are implemented first in regions where the RF reduction is the greatest per ton abated BC. In scenario 2, the cost-effectiveness across regions is also taken into account. Emissions are reduced in regions (and

sources) where the marginal abatement costs are the lowest while maximizing the climate benefit. Scenario 3 introduces the ability to pay by scaling regional abatement costs linearly by relative gross domestic product (GDP) per capita. Each scenario is considered under three different targets: reducing RF by 10, 20 and 30% (named RF10, RF20 and RF30). Finally, three versions of all scenarios are run with respect to the climate effect. The first only takes into account the direct climate effect (“direct GWP only”). The second, called “total GWP”, includes the indirect effect of BC deposited on snow and ice. The third version (“Efficacy”) includes the enhanced climate efficacy of BC deposited on snow by multiplying the indirect GWP with an efficacy factor of 3. In total 27 runs were made as shown in Table 14.

**Table 14 Emission reductions (kt/yr) and total annual costs (billion €) for analyzed scenarios and reductions in BC RF**

	10 %				20 %				30 %			
	BC	OC	PM <sub>10</sub>	Costs	BC	OC	PM <sub>10</sub>	Costs	BC	OC	PM <sub>10</sub>	Costs
<b>Direct GWP only</b>												
S1	310	268	7254	43	668	649	11463	196	1146	1057	31039	300
S2	418	357	2978	3	775	555	11132	23	1166	743	35477	98
S3	450	310	2667	10	833	584	26010	43	1189	803	35645	120
<b>Total GWP</b>												
S1	310	268	7254	43	688	683	11551	214	1143	1113	16129	328
S2	416	380	4113	3	775	556	11060	23	1164	747	35590	97
S3	444	309	2579	10	829	584	26001	42	1183	803	35669	118
<b>Efficacy</b>												
S1	310	246	8593	44	661	581	11797	178	1121	1111	15767	353
S2	410	378	4059	2	769	556	11129	22	1153	767	36446	92
S3	426	307	2791	9	811	579	25817	40	1167	782	35276	114

Table 14 shows the emission reductions (kt/yr) and total annual costs (billion €) for the three different scenarios (S1, S2, S3) and targets (10%, 20% and 30% reduction in RF), taking into account different climate effects (direct effect, indirect effect on snow, and climate efficacy).

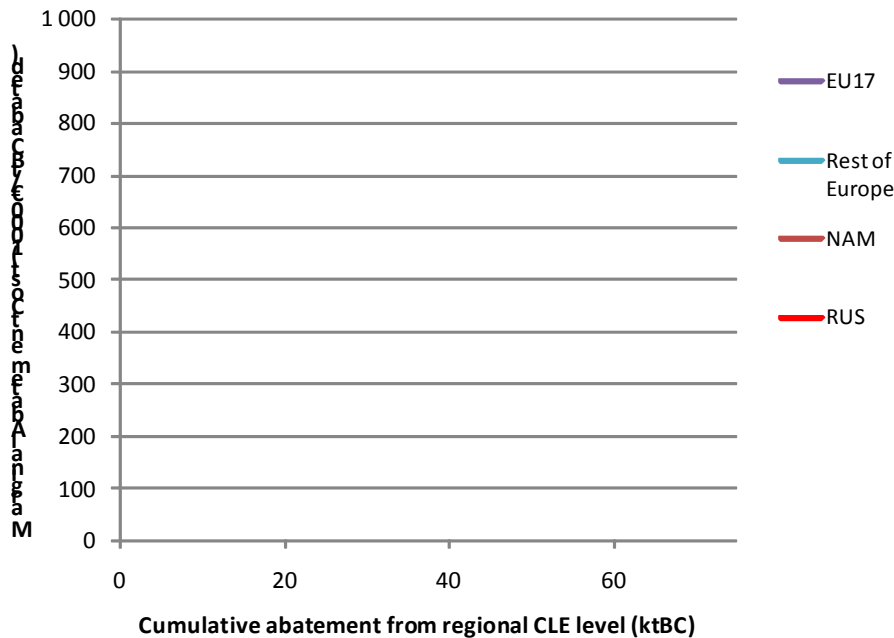
In S1, mitigation takes place first in the regions with the highest GWP. Only considering the direct climate effect, the most effective strategy is to first mitigate in AFR, MIDE and SAS. EU17, RoE and NAM are tied as the 6<sup>th</sup>-8<sup>th</sup> regions to be abated, while RUS is abated last. However, when the full climate effects (including both indirect effect on snow and the climate efficacy) are taken into consideration, MIDE and SAS are abated first followed by RUS (3) and RoE (4). EU17 and NAM are tied 6<sup>th</sup> after AFR (5). The reductions in S1 are very expensive, since all abatement potential is exhausted in one region before moving on to the next.

In S2 the cost effectiveness across regions is taken into account, thus representing a more realistic scenario than S1. Here the most effective strategy is to introduce reductions first in Asia. If RF is to be reduced by 10% (direct GWP only), then almost 50% of the global abatement effort should take place in CPA and 18% in SAS, while only 7% in Europe. For RF20, these figures are 31% for CPA, 23% for SAS and 8% for Europe. If the full climate effects are taken into account in the RF20 case, the European reduction burden only increases to 10%, while the Asian burden is approximately the same. Consequently, consideration of the indirect component of the GWP and

climate efficacy would not be a very important factor in shifting regional abatement efforts when cost-effectiveness is included in the analysis.

S3 takes into consideration the ability to pay for reductions. Here the optimal abatement efforts are shifted from SAS and AFR to richer regions (although there is little change or an increase in abatement for China compared to S2). Efforts in EU17, RUS and NAM should increase by 40-60% compared to S2 (under RF20).

Overall, the optimal abatement strategy from a climate and total global cost perspective is to prioritize abatement of BC emissions in Asia. Asia is responsible for a large share of total emissions and has lower abatement costs compared to Europe and North America. In addition, reductions of BC in Asia also give the highest co-benefits in terms of reduced PM<sub>10</sub> emissions. Considering the indirect climate effect and especially the efficacies of BC deposited on snow provide stronger justification for abatement in the Arctic countries.



**Figure 17 Marginal abatement curves for BC in near-Arctic regions (derived from Rypdal et al., 2009)**

***CO<sub>2</sub> equivalent metrics***

There is a demand for a metric that can be used to convert from BC marginal abatement costs into CO<sub>2</sub> equivalent abatement costs. There are significant reasons for concern in developing such a metric, given the numerous differences between a long-lived well-mixed gas and a short-lived aerosol; however there have been several estimates of various metrics of comparison between BC and CO<sub>2</sub> emissions. Metrics based on integrating either reductions or forcings over 100 year timescales show per ton black carbon reductions having an impact ranging from 330 (Jacobson 2005) to 2240 (Jacobson 2007) that of per ton CO<sub>2</sub> reductions. However, this fairly wide span of values is perhaps misleading: the lowest estimates are metrics for “fossil soot” (a mixture of BC and OC), some estimates include the snow albedo effect, some are location dependent, some are temperature based where others are radiation based, and some use a drastically different carbon cycle model. More central estimates range from about 500 to about 1300 (Rypdal et al 2009,

Boucher et al. 2008, Bond et al. 2008). In addition, some modelers argue that because BC reductions are being proposed to address short term climate change, BC should be measured in the short term: 20 year GWPs would yield CO<sub>2</sub> equivalent values for BC 3.5 times higher than 100 GWPs based on the Bern carbon cycle approximation. Alternatively, due to the long term nature of the climate problem, other researches have proposed using 500 year GWPs, or GTP-pulse methods (Shine et al. 2005), which would yield CO<sub>2</sub> equivalents values for BC a factor of 3 to 7 smaller. Because the climate efficacy of BC emissions depends on the location from which they are emitted, Rypdal et al. (2009) also calculate differing GWPs for different regions.

Because a short-lived particulate like BC has properties that are very different from the well-mixed gases, it may be premature to attempt to include BC in a basket of gases using these GWP estimates for trading purposes. However, these estimates can still serve a valuable purpose as an illustrative measure. Along those lines, we can compare BC mitigation costs with carbon mitigation costs. For example, the carbon price in the EU ETS is currently about \$16 per tonne CO<sub>2</sub> (about \$60 per tonne C). At a GWP of 500, that would be \$8000/tonne BC. At a GWP of 1300, the EU ETS CO<sub>2</sub> equivalent price would be about \$21,000/ton BC. At the upper end of this range, retrofitting most Class 8b trucks is cost-effective for the global warming benefits alone, even without including air quality co-benefits. Carbon prices are also expected to rise in the near term, making more ambitious mitigation options cost effective. These estimates do not take into account any mitigating temperature effects from co-emissions of OC or SO<sub>2</sub>.

In the U.S., it is more difficult to assign economic costs to certain agricultural measures, but estimates indicate that for about \$12,000 dollars a tonne BC 28,000 tonnes of BC can be reduced from agricultural burning in the U.S. (along with 165,000 tonnes of OC). The Rypdal et al. (2009) analysis shows that about 80,000 tons of BC reductions are available for less than \$20,000 a ton BC between the EU17, RoE, North America, and Russian regions.

## **7. Policy Options within Arctic Nations and for Pan-Arctic Mitigation Strategies**

**[Note: this section will be completed in a final draft and will discuss existing policy forums such as UNFCCC, LRTAP, IMO or others]**

## **8. Identification of Key Uncertainties, Gaps in the Analysis**

The results in this ad hoc working paper are in some cases preliminary. In addition, a number of areas have been identified as requiring further research. The overall impact of BC emissions on climate continues to be uncertain. Improvements in inventories and projections for sectors such as oil and gas flaring, industrial emissions, and shipping will enable better judgments of mitigation potentials from those sectors. Similarly, improvements in atmospheric transport modeling will improve the ability to prioritize emissions reductions where they will have the most impact per ton BC reduced at the source. Net climate impacts on the Arctic for sources with low BC:OC ratios still need to be determined more accurately.

On the cost side, the U.S. results generated with the draft MOVES model are preliminary. Cost data acquired from the current retrofit programs will lead to improvements in estimating marginal abatement curves. In the case of biomass burning, understanding the non-market barriers to implementation and stakeholder communication may be as important as further research into mitigation costs.

## **9. Discussion of Most Promising Mitigation Options**

**[Note: this section will be completed in a final draft]**

## APPENDICES

### Health Effects of Particulate and Black Carbon Emissions

#### *Black carbon as a component of fine particulate*

Fine particles in the atmosphere are made up of a complex mixture of components, including black carbon. Other common constituents include: sulfate ( $\text{SO}_4^{2-}$ ); nitrate ( $\text{NO}_3^-$ ); ammonium ( $\text{NH}_4^+$ ); organic compounds; and inorganic material (including metals, dust, sea salt, and other trace elements). Fine particles have a nominal aerodynamic diameter of 2.5 micrometers or less (a micrometer is one-millionth of a meter, and 2.5 micrometers is less than one-seventh the average width of a human hair) and are also known as  $\text{PM}_{2.5}$ . “Primary” particles are emitted directly into the air as a solid or liquid particle (e.g., black carbon from diesel engines or fire activities, or condensable organic particles from gasoline engines). “Secondary” particles (e.g., sulfate and nitrate) form in the atmosphere as a result of various chemical reactions. [PM implementation NFR 4-07]

$\text{PM}_{2.5}$  components vary considerably by geography and species. Variability in  $\text{PM}_{2.5}$  components across the U.S. was recently examined by focusing on fifteen metropolitan areas. On an annual average basis, sulfate was the dominant  $\text{PM}_{2.5}$  component in cities east of Houston and ranges from 42% to 56% of  $\text{PM}_{2.5}$  mass. Organic carbon mass (OCM) was the next largest component in the east. In the western cities, OCM was the largest constituent of  $\text{PM}_{2.5}$  on an annual basis, ranging from 34% in Los Angeles to 58% in Seattle. Contributions of sulfate, nitrate and crustal material (derived from common oxides contained in the Earth’s crust) to  $\text{PM}_{2.5}$  mass varied in the western cities examined. BC (or “EC” elemental carbon) makes up a smaller fraction of the  $\text{PM}_{2.5}$  (4 to 11%), but it is consistently present in all of the 15 included cities, regardless of region.

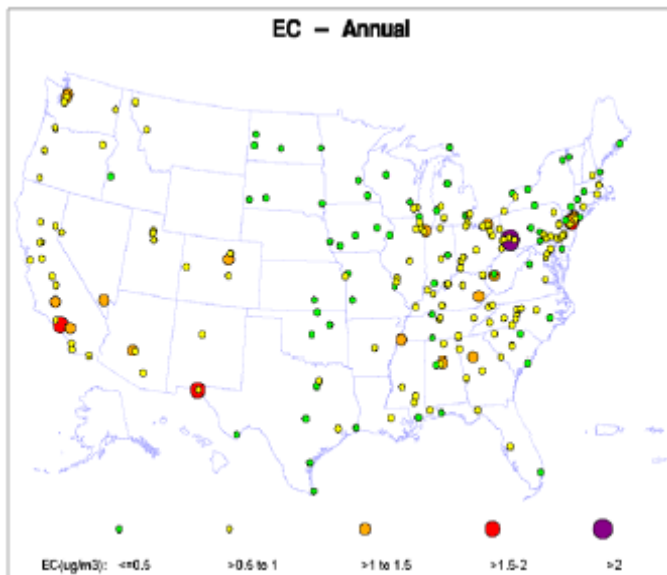


Figure 18 EC concentrations measured at CSN sites across the U.S., 2005-2007, shows there are isolated monitors spread throughout the US that measure high annual average EC levels. These EC ‘hot spots’ are primarily associated with larger metropolitan areas such as Los Angeles, Pittsburgh, and New York, but El Paso, TX, also reported high annual average EC levels (driven by a wintertime average concentration greater than  $2 \mu\text{g}/\text{m}^3$ ). [From 12-08 PM ISA]

*Health indicator includes mass of all fine particle components*

In 1997, EPA established PM<sub>2.5</sub> as the National Ambient Air Quality Standards (NAAQS) indicator for fine particles. In reaching this decision, the Agency first considered whether the indicator should be based on the mass of a size-differentiated sample of fine particles or on one or more components within the mix of fine particles. The EPA determined that it was more appropriate to control fine particles as a group, as opposed to singling out any particular component or class of fine particles. Community health studies had found significant associations between various indicators of fine particles and health effects in areas with significant mass contributions of differing components or sources of fine particles, including sulfates, wood smoke, nitrates, secondary organic compounds and acid sulfate aerosols. In addition, a number of animal toxicologic and controlled human exposure studies had reported health effects associations with high concentrations of numerous fine particle components (e.g., sulfates, nitrates, transition metals, organic compounds), although such associations were not consistently observed. It also was not possible to rule out any component within the mix of fine particles as not contributing to the fine particle effects found in epidemiologic studies. For these reasons, EPA concluded that total mass of fine particles was the most appropriate indicator for fine particle standards rather than an indicator based on PM composition (62 FR 38667, July 18, 1997). [2006 Staff Report]

*Health effects associated with fine particles*

In 1997 and in a subsequent review in 2006, EPA based the fine particle standards on significant evidence and numerous health studies demonstrating that serious health effects are associated with exposures to elevated levels of PM<sub>2.5</sub>. Epidemiological studies have shown positive associations between PM<sub>2.5</sub> concentrations and premature mortality. Other important effects associated with PM<sub>2.5</sub> exposure include aggravation of respiratory and cardiovascular disease (as indicated by increased hospital admissions, emergency room visits, absences from school or work, and restricted activity days), changes in lung function and increased respiratory symptoms, as well as new evidence for more subtle indicators of cardiovascular health. Individuals particularly sensitive to PM<sub>2.5</sub> exposure include older adults, people with heart and lung disease, and children. [PM implementation NFR 4-07]

Attainment of the PM<sub>2.5</sub> standards in the U.S. is estimated to lead to reductions in health impacts, including tens of thousands fewer premature deaths each year, thousands fewer hospital admissions and emergency room visits each year, hundreds of thousands fewer absences from work and school, and hundreds of thousands fewer respiratory illnesses in children annually. The EPA's evaluations of the science concluded that there was not sufficient information to either support or refute the existence of a threshold for health effects from PM exposure; i.e., emissions reductions resulting in reduced concentrations below the level of the standards may continue to provide additional health benefits to the local population. [PM implementation NPR 11-05]

In December 2005, EPA described the available health effects evidence in detail (PM Staff Paper). Short-term exposure to PM<sub>2.5</sub> is likely causally associated with mortality from cardiopulmonary diseases, hospitalization and emergency department visits for cardiopulmonary diseases, increased respiratory symptoms, decreased lung function, and physiological changes or biomarkers for cardiac changes. Long-term exposure to PM<sub>2.5</sub> is likely causally associated with mortality from cardiopulmonary diseases and lung cancer, and effects on the respiratory system such as decreased lung function or the development of chronic respiratory disease.

*The latest scientific knowledge on fine particle health effects*

In December 2008, EPA prepared a document which serves to form the scientific foundation for the review of the primary (health-based) and secondary (welfare-based) NAAQS for PM. The first external review draft Integrated Science Assessment (ISA) is a concise review, synthesis, and evaluation of the most policy-relevant science, and communicates critical science judgments relevant to the NAAQS review. All relevant epidemiologic, human clinical, and animal toxicological studies published since the last review were considered.

This document includes the following information (primarily from Section 2.3, Health Effects).

The large body of evidence from studies that examined the effect of short-term exposure to PM<sub>2.5</sub> on cardiovascular morbidity found consistent effects across epidemiologic, human clinical and toxicological studies. The consistent and coherent results from epidemiologic, human clinical, and toxicological studies provides sufficient evidence to conclude that a causal relationship exists between short-term exposure to ambient concentrations of PM<sub>2.5</sub> and cardiovascular morbidity.

The epidemiology studies that examined the association between short-term exposure to PM<sub>2.5</sub> and respiratory morbidity found the most consistent associations with (1) asthmatic children and respiratory symptoms/medication use and (2) older adults and hospital admissions/emergency department visits for respiratory diseases. Numerous respiratory responses were observed in both the human clinical and toxicological studies that provide biological plausibility. The consistent and coherent results found in the epidemiologic, human clinical, and toxicological literature provide sufficient evidence to conclude that a causal relationship is likely to exist between short-term exposures to ambient concentrations of PM<sub>2.5</sub> and respiratory morbidity.

An evaluation of the epidemiologic literature indicates consistent positive associations between short-term exposure to PM<sub>2.5</sub> and all-cause (non-accidental), respiratory- and cardiovascular-related mortality. The epidemiologic evidence, along with the results from the examination of potential confounders and effect modifiers of the PM<sub>2.5</sub>-mortality relationship, provide sufficient evidence to conclude that a causal relationship is likely to exist between short-term exposure to ambient concentrations of PM<sub>2.5</sub> and mortality.

Epidemiologic and toxicological studies have provided evidence of the adverse effects of long-term exposure to PM<sub>2.5</sub> on clinical and subclinical markers of cardiovascular morbidity. Furthermore, the evidence from cardiovascular outcomes associated with short-term exposure to PM<sub>2.5</sub> supports a role for the development of cardiovascular disease in response to long-term exposure to PM<sub>2.5</sub>. Based on the consistent and coherent evidence from epidemiologic and toxicological studies that examined the association between long-term and short-term exposure to PM<sub>2.5</sub> and cardiovascular morbidity, sufficient evidence is available to conclude that a causal relationship is likely to exist between long-term exposure to ambient concentrations of PM<sub>2.5</sub> and cardiovascular morbidity.

Recent epidemiologic studies provide consistent evidence of association between long-term exposure to PM<sub>2.5</sub> and respiratory symptoms, asthma, and decrements in lung function growth in children. Results from toxicological studies provide biological plausibility for the development of respiratory-related health effects from long-term exposure to PM<sub>2.5</sub>. Overall, the consistent and coherent evidence from epidemiologic and toxicological studies is sufficient to conclude that a causal relationship is likely to exist between long-term exposure to ambient concentrations of PM<sub>2.5</sub> and respiratory morbidity.

New epidemiologic evidence reports a consistent association between long-term exposure to PM<sub>2.5</sub> and increased risk of mortality. Recent results from the Harvard Six Cities cohort study shows a relatively large reduction in mortality risk associated with a decrease in PM<sub>2.5</sub> concentrations. Additional analyses of the Harvard Six Cities cohort and the American Cancer Society (ACS) study in Los Angeles suggest that previous and current studies may have underestimated the magnitude of the PM<sub>2.5</sub>-mortality association. Overall, the consistent evidence reported across epidemiologic studies is sufficient to conclude that a causal relationship is likely to exist between long-term exposure to ambient concentrations of PM<sub>2.5</sub> and mortality.

Recently, epidemiologic, human clinical and toxicological studies have begun to evaluate the health effects associated with ambient PM constituents and sources, as opposed to PM mass. Collectively, a consistent trend or pattern that links particular constituents or sources with specific health outcomes was not observed, but a number of PM<sub>2.5</sub> constituent groupings that are commonly associated with sources such as crustal/soil, salt, secondary sulfate/long-range transport, traffic, oil combustion and wood smoke/vegetative burning were linked with health effects.

## **Additional Inventories and Projections**

We include here some of the other inventories of black carbon that have been published in recent years.

**Table 15 Black Carbon and Organic Carbon emissions for near-Arctic regions in 1996 (Streets, Bond et al. 2004)**

Gg/year	BC	OC	OC:BC Ratio
Canada	93	772	8.3
United States	414	1476	3.6
OECD Europe	392	1032	2.6
Eastern Europe	137	310	2.3
Former USSR	282	1629	5.8

**Table 16 Contained and Open Black Carbon and Organic Carbon emissions from near-Arctic regions in 1996 (Bond, Streets et al. 2004)**

Gg/year		BC	OC	OC:BC Ratio
North America	Contained	382	575	1.5
	Open	116	1473	13
Europe	Contained	466	572	1.2
	Open	59	691	12
Former USSR	Contained	178	225	1.3
	Open	100	1245	12

The Bond and Streets inventories are not entirely independent but they break the emissions down differently: Streets has slightly more regional resolution, but Bond divides emissions into contained combustion sources (both fossil and biofuel) and open combustion sources. Examination of the two inventories presents clear pictures: open burning, mostly agricultural, has high OC:BC ratios, and therefore mitigation measures targeting these sources are only likely to have significant cooling effects in regions that are snow covered. Contained combustion sources in northern regions produce the majority of the BC emissions from those areas, but significantly less than half of the OC. Therefore, controlling these contained combustion sources is likely to produce a greater net climate benefit.

Cofala et al (2007) estimated global historical (1990, 1995, 2000) emissions and developed two scenarios up to 2030 (Table 17). The baseline projection (CLE) assumes implementation of the already decided emission control legislation in each country, based on the current (end of 2003) national expectations of economic development. The alternative scenario (MFR) explores the emission reductions that could be achieved, for the same assumptions on the economic development, with the most advanced emission control technologies implemented in the GAINS model. For BC the only significant difference between this assessment and the GAINS 2008 assessment presented in the main text is for Russia and NIS - the more recent calculation includes new assessment of flaring. For OC the differences are larger owing primarily to modified emission factors in the domestic sector. The higher increase in the recent GAINS assessment for Russia is the result of updated Russian energy projection including also increase in flaring emissions as only minor autonomous improvement in this sector has been assumed. For Europe, the GAINS calculates in CLE case slightly more reduction (compared to Cofala et al.) for Western Europe and much less for Central/Eastern Europe. There are two main reasons for that: stricter legislation in transportation, introduction of the climate energy package (-20% of CO<sub>2</sub> by 2020 in the European Union), but at the same time a revision of activity projections for several Central and Eastern European countries showing higher growth.

**Table 17 Emissions of BC and OC for selected regions after Cofala et al (2007)**

units kt	Current Legislation					Maximum Feasible Reduction		
	1990	2000	2010	2020	2030	2010	2020	2030
BC:								
North America	322	280	244	193	181	82	89	95
Western Europe	412	387	268	207	177	243	160	118
Central/Eastern Europe	134	99	73	54	48	53	32	25
Russia and NIS	527	219	262	251	264	120	114	116
OC:	Current Legislation					Maximum Feasible Reduction		
	1990	2000	2010	2020	2030	2010	2020	2030
North America	444	354	299	268	267	101	115	132
Western Europe	623	502	428	372	325	341	284	241
Central/Eastern Europe	268	183	144	115	102	88	64	54
Russia and NIS	887	367	451	434	428	105	99	100

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